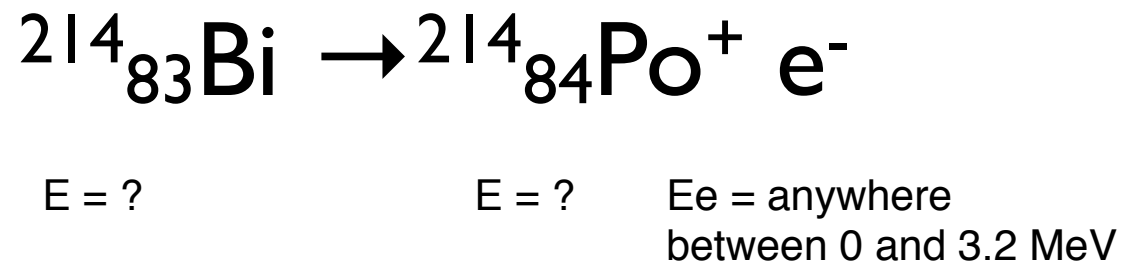
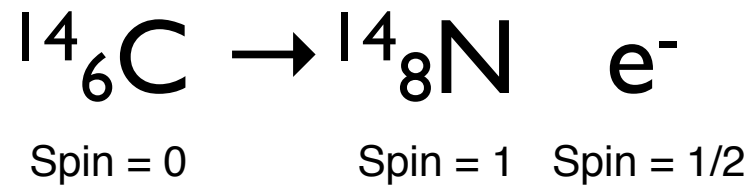


Recent results from Project 8

Ben Monreal, UCSB

Studying neutrinos without detecting them



In Fig. 1, the end of the distribution curve for $\mu=0$ and for large and small values of μ is sketched. The greatest similarity to the empirical curves is given by the theoretical curve for $\mu=0$.

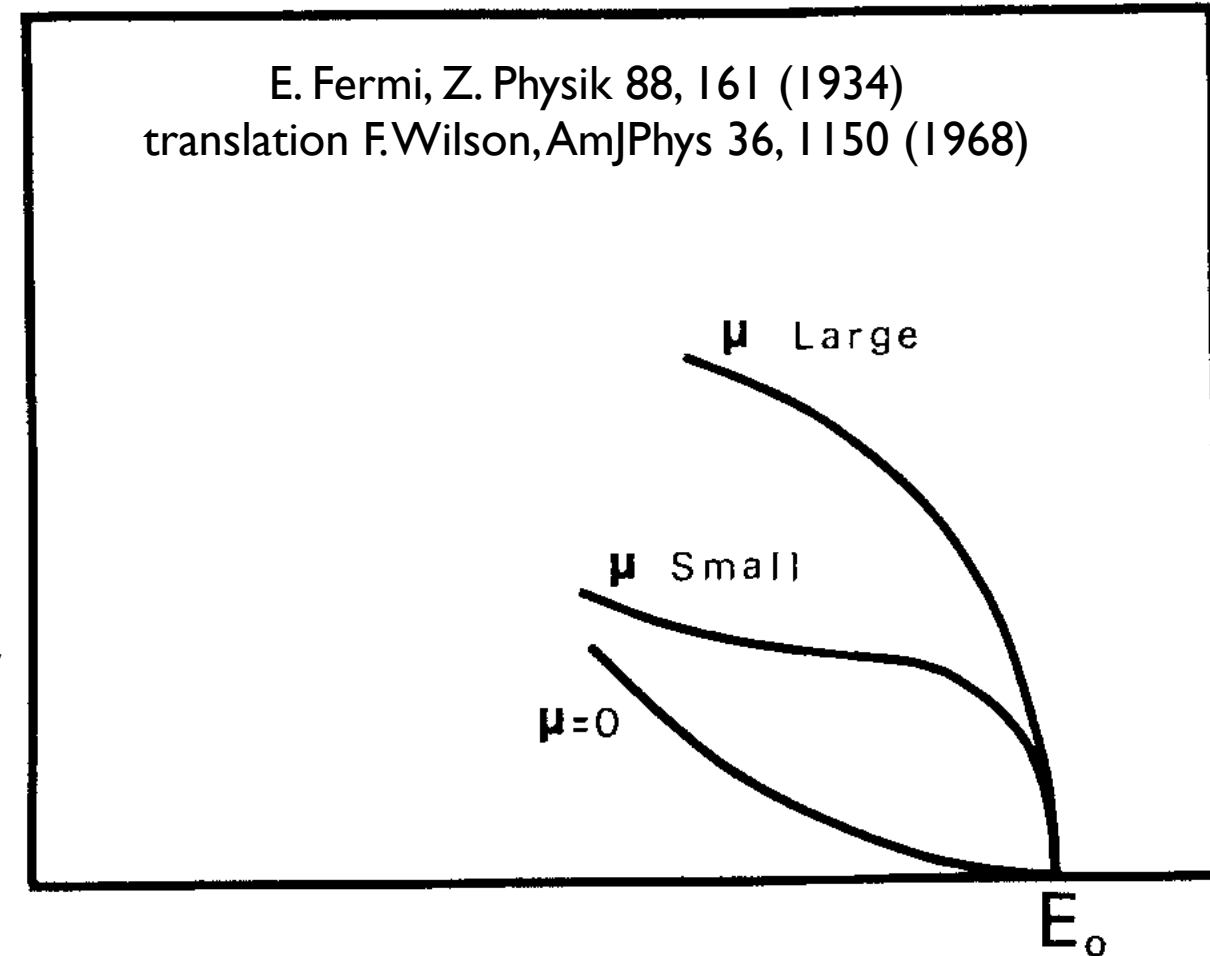
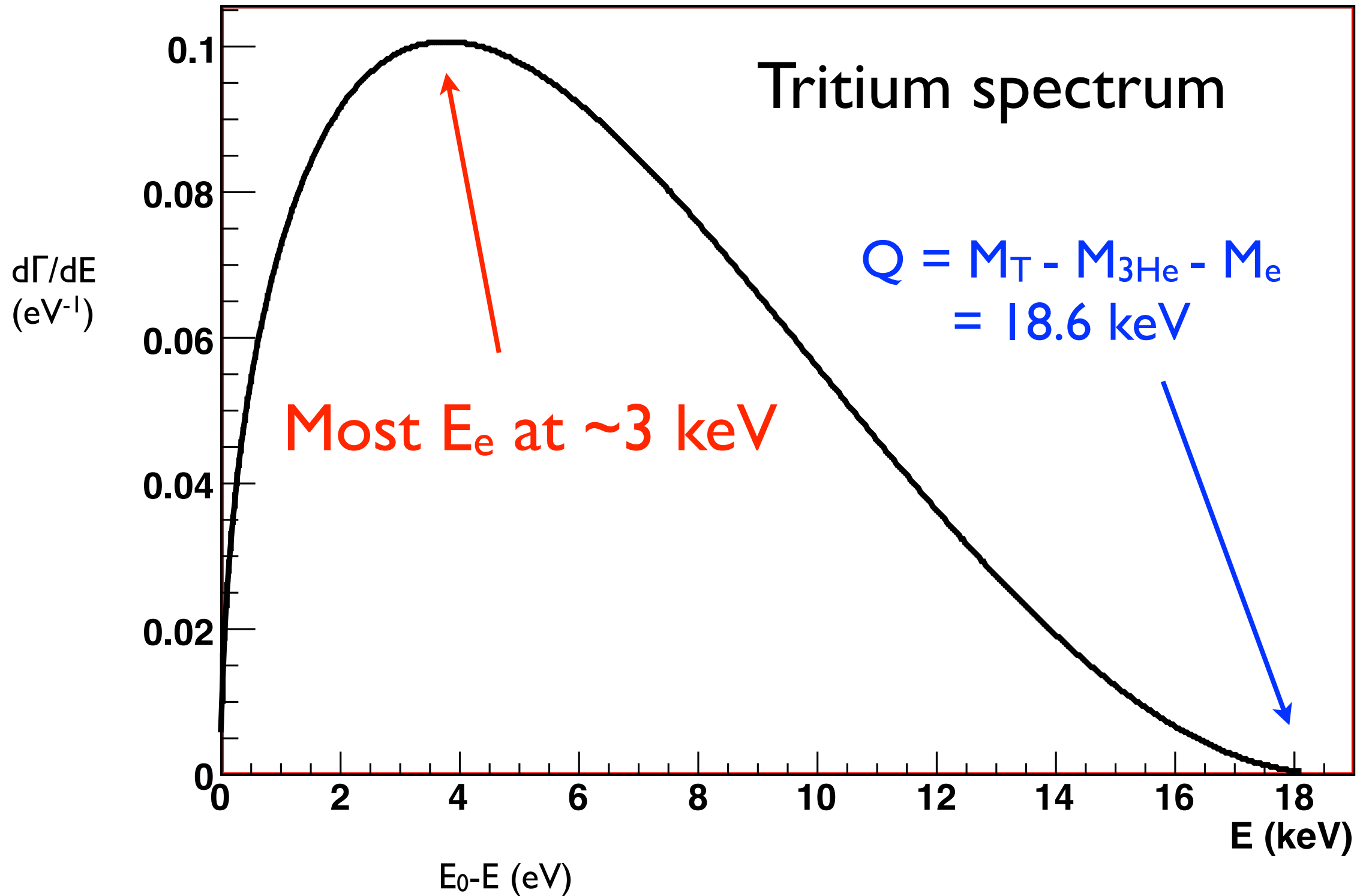


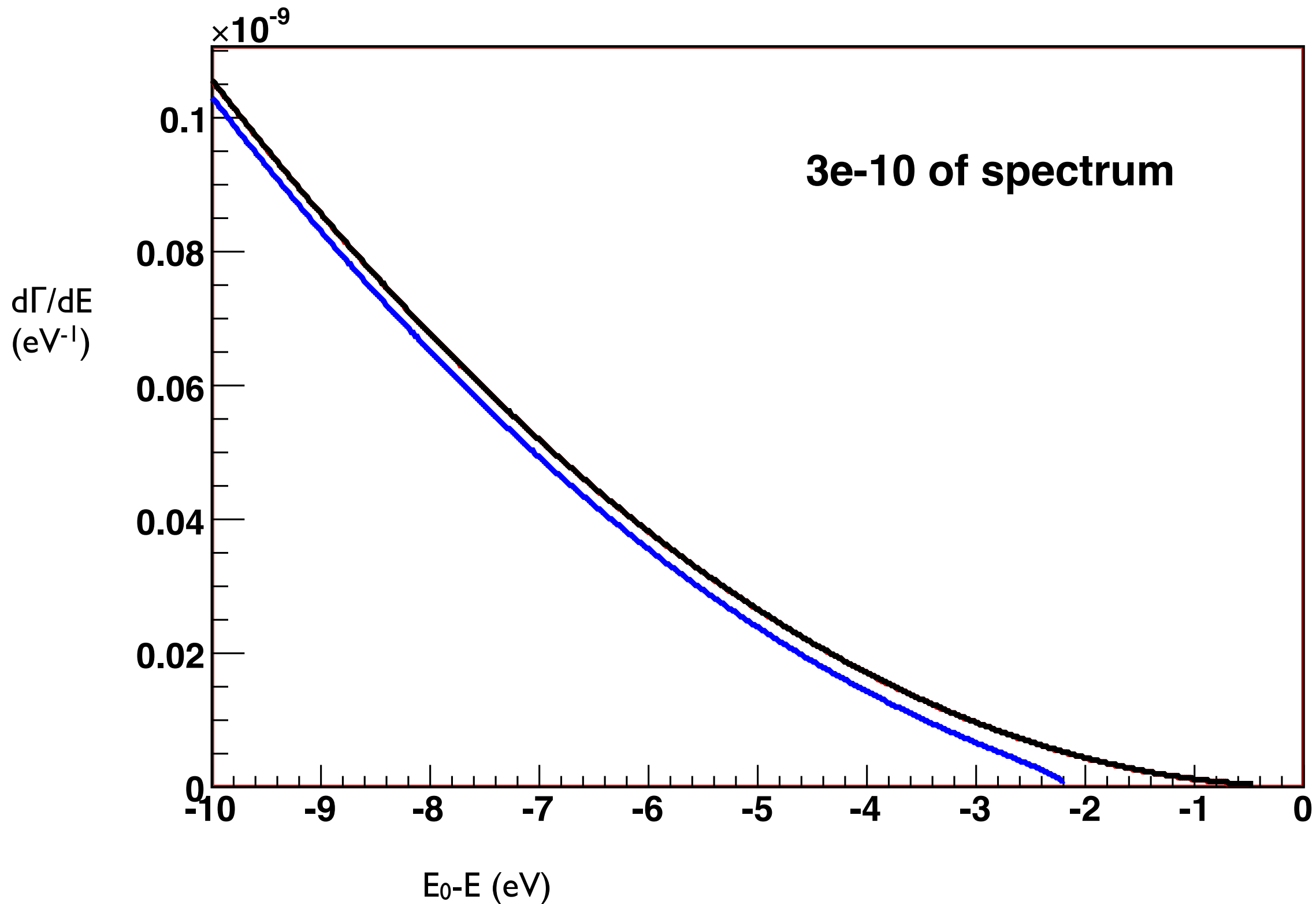
FIG. 1. The end of the distribution curve for $\mu=0$ and for large and small values of μ .

Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron.¹⁰ In the

Current limit 2.0 eV, BR < 10⁻¹⁰



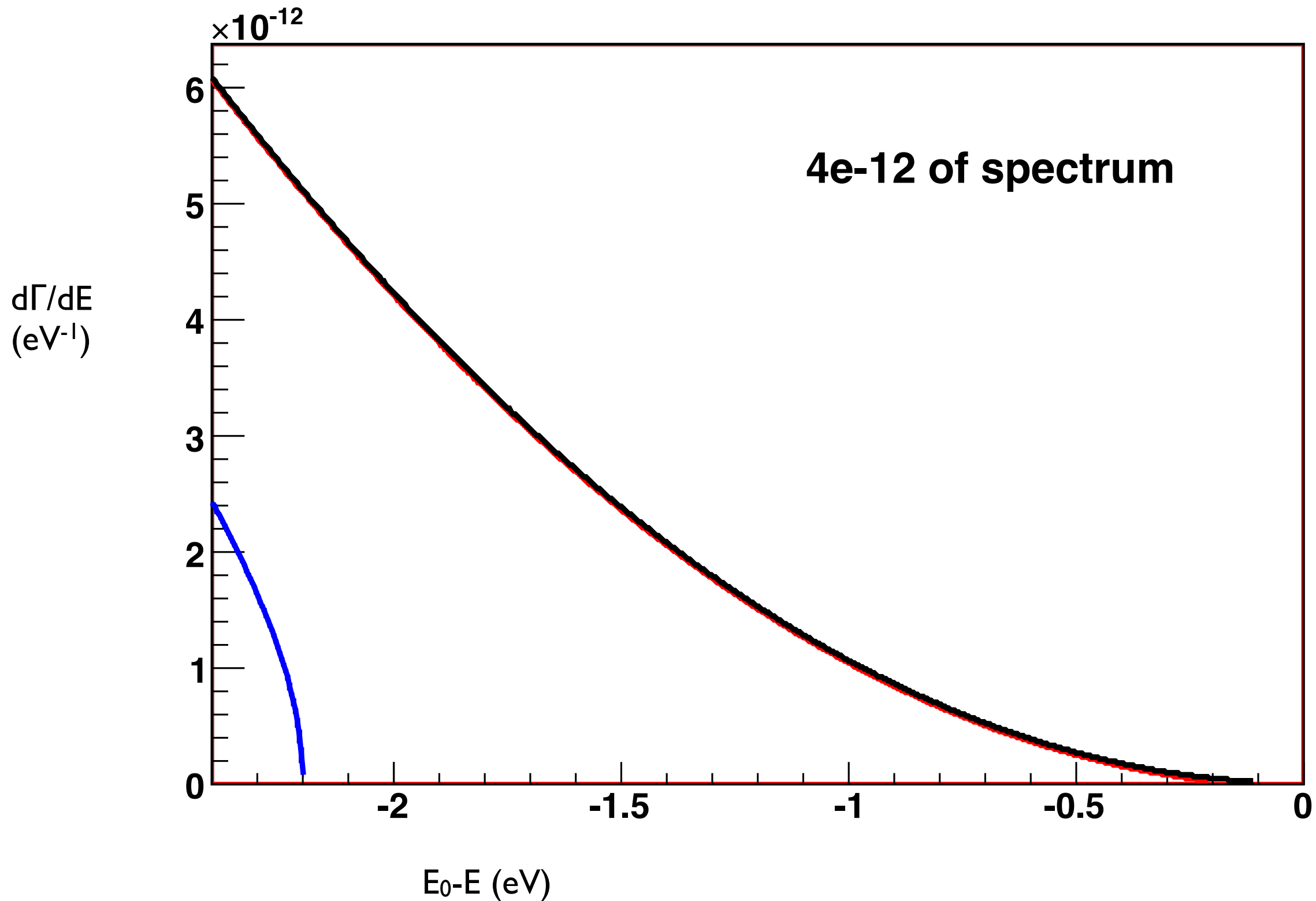
Current limit 2.0 eV, BR < 10⁻¹⁰



Current limit 2.0 eV, BR < 10⁻¹⁰



KATRIN goal 0.2 eV, BR < 10⁻¹²

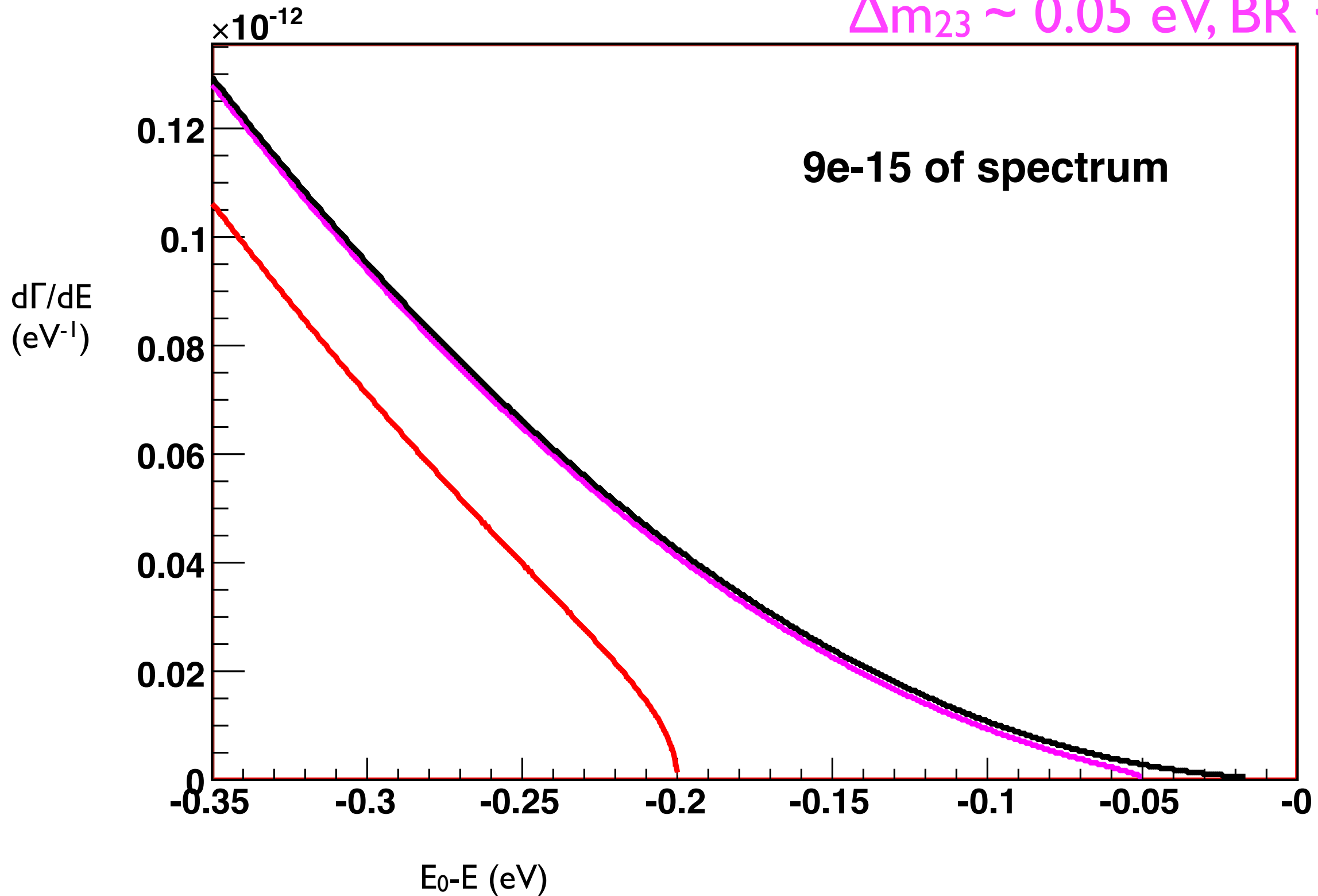




Current limit 2.0 eV, BR < 10^{-10}

KATRIN goal 0.2 eV, BR < 10^{-12}

$\Delta m_{23} \sim 0.05$ eV, BR < 10^{-14}



KATRIN

(KArlsruhe TRItium Neutrino)



KATRIN experiment

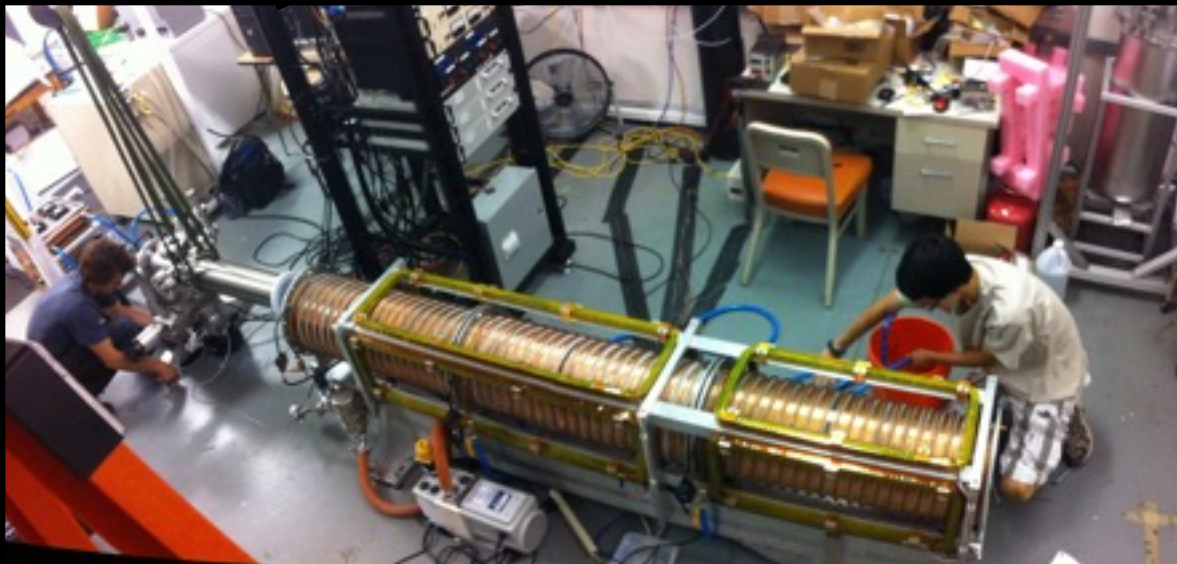
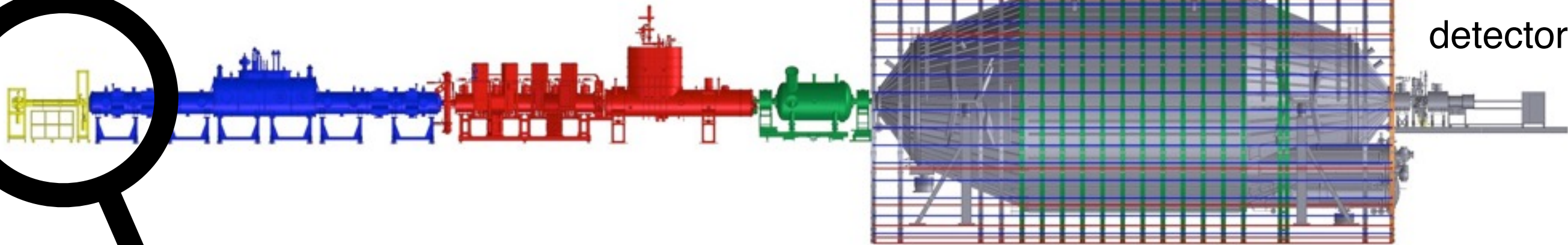
Goal: $m_\nu = 0.2$ eV sensitivity

Tritium source
 10^{11} decays/second

magnetic transport
of electrons

Electrostatic
high-pass filter
0.9 eV-wide cutoff

detector



UCSB-built calibration gun



Shipped to Germany Feb 2015

Why KATRIN doesn't scale up well

Source strength = r^2

Statistical error = r^1

Viscous flow rate = r^4

Pumping area = r^2

Molecular flow rate = r^3

Plasma charging = rL Need very long source to pump adequately, $L \sim r^{1+}$

Magnet cost $(r^2 L)^{0.6} = r^{1.8++}$

Spectrometer radius = r^1

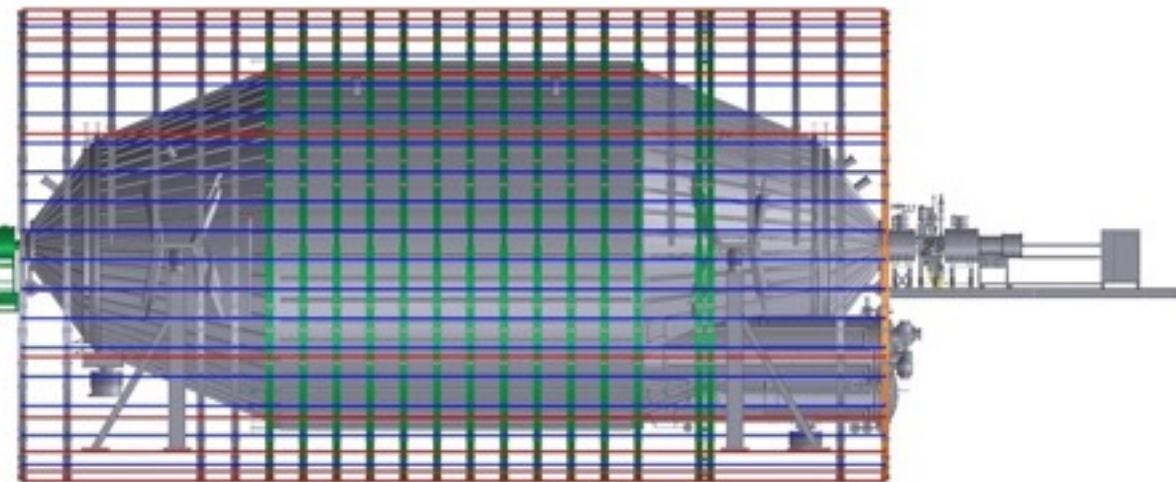
Expensive, thick-wall
Unprecedented size

Spectrometer area = r^2

Vacuum load \sim area
Whole area needs instrumenting

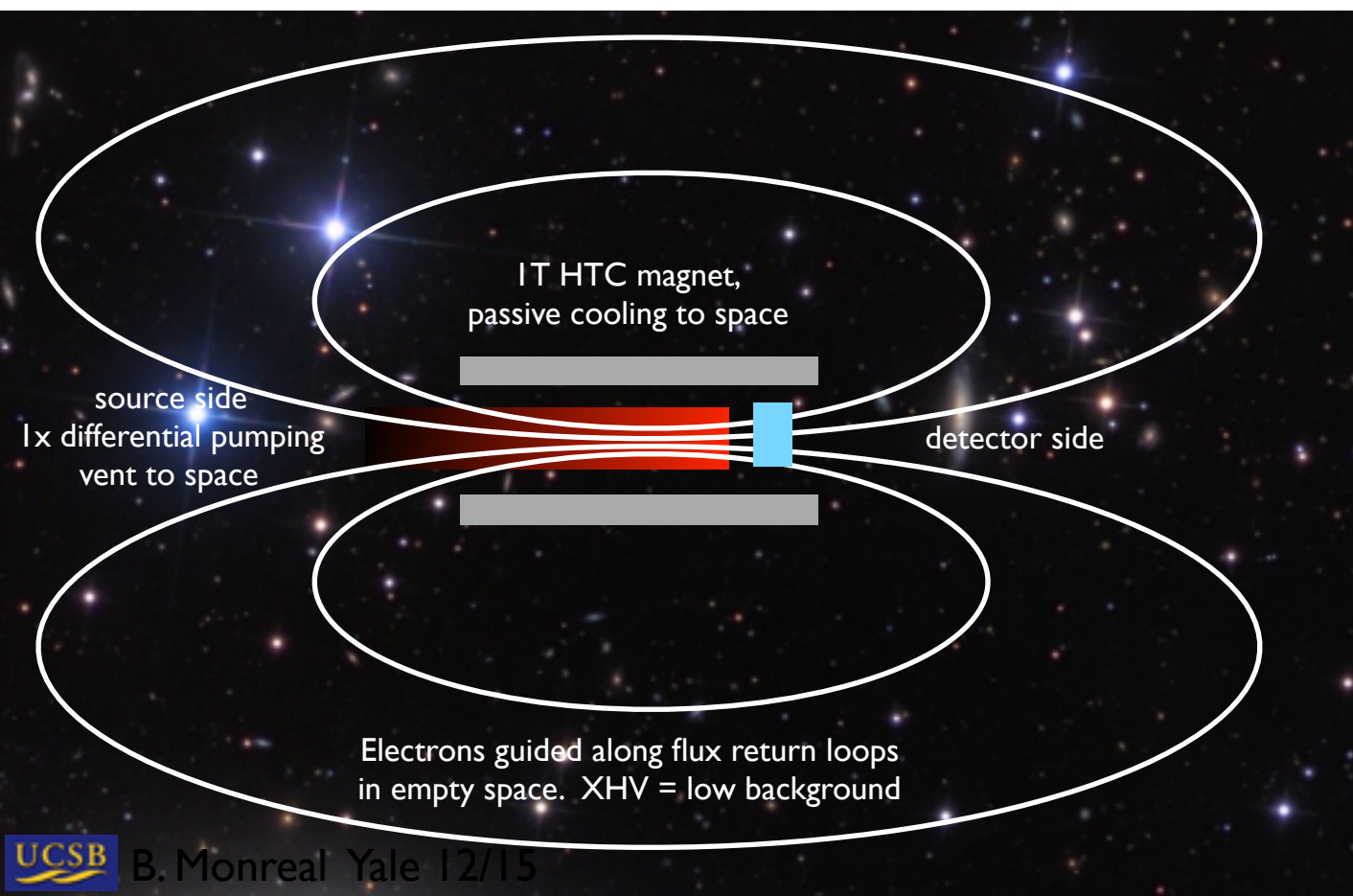
Spectrometer volume = r^3

Whole volume is a background source



Harder to clear
Penning/bottle traps = $r^{??}$

Detector-related backgrounds = r^2



SpaceTRIN* is probably easier than 3-folding KATRIN

(*I am making this up)

The Project 8 concept

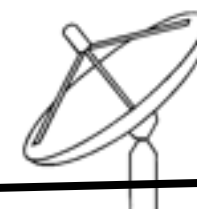
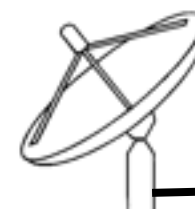
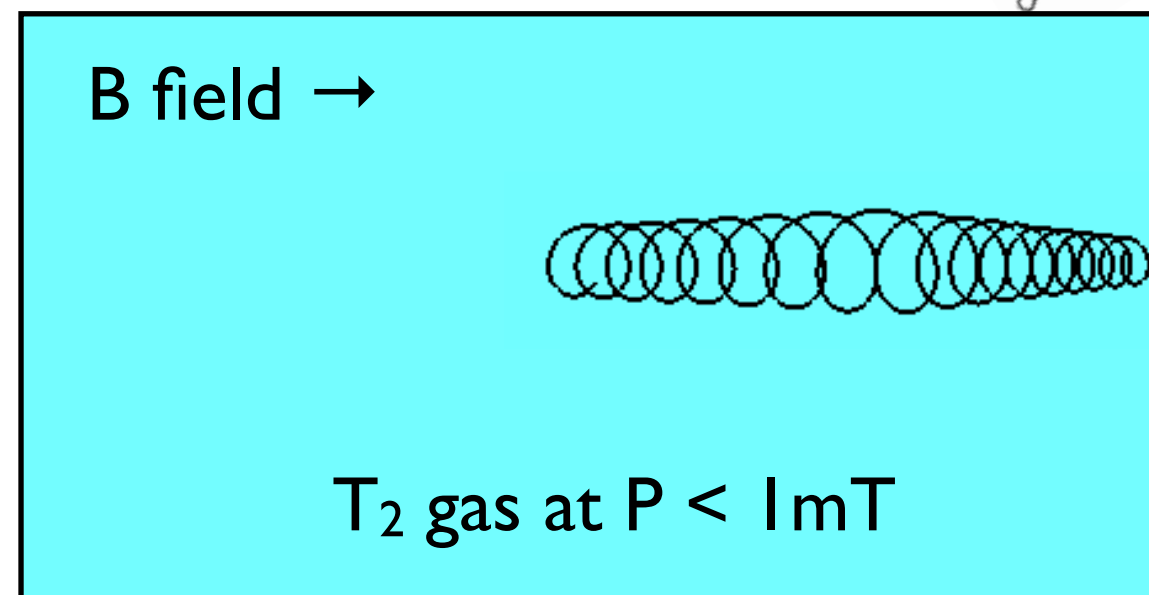
Cyclotron radiation

- emitted by mildly relativistic electrons
- Coherent, narrowband
- 10^{-15} W per electron

$$P_{\text{tot}} = \frac{1}{4\pi\epsilon_0} \frac{2q^2\omega_c^2}{3c} \frac{\beta_{\perp}^2}{1-\beta^2}$$

- Electron energy contributes to velocity v , power P , frequency ω
- *Can we detect this radiation, measure v , P , ω , and determine $E \pm 1$ eV?*

$$f_{\gamma} = \frac{f_c}{\gamma} = \frac{eB}{2\pi(m_e + K/c^2)}$$

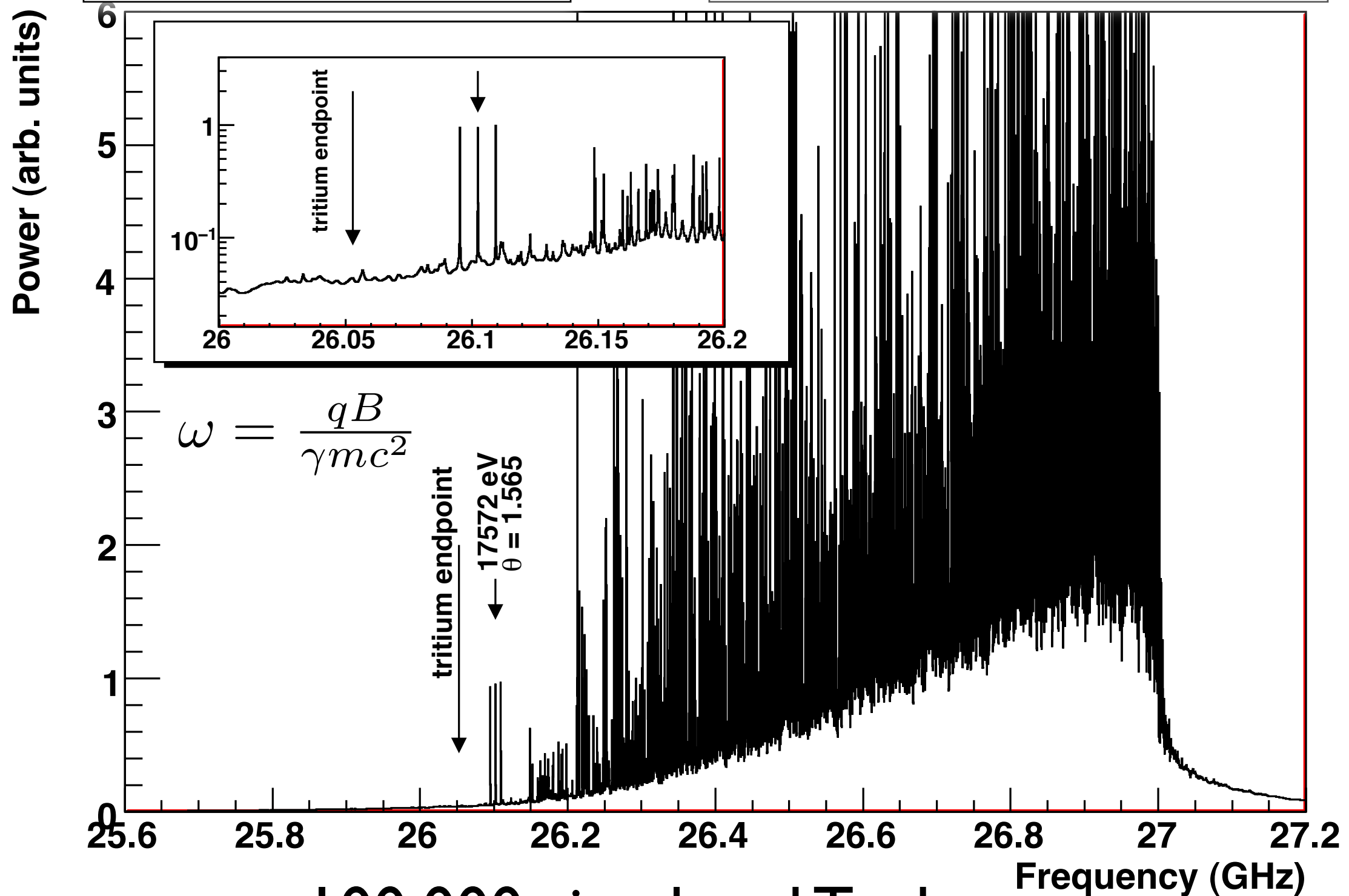


Microwave antennae



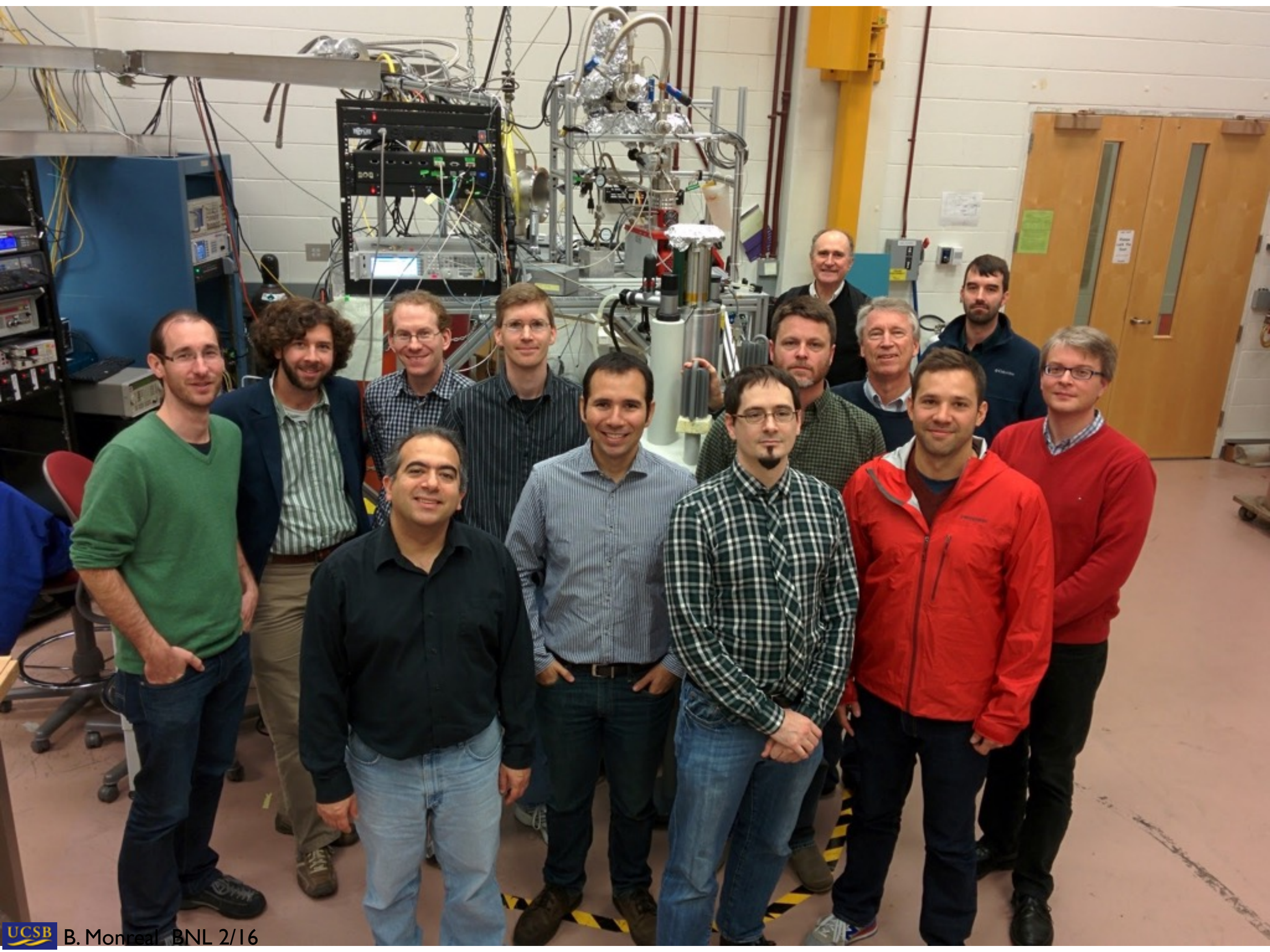
rare high-energy
electrons

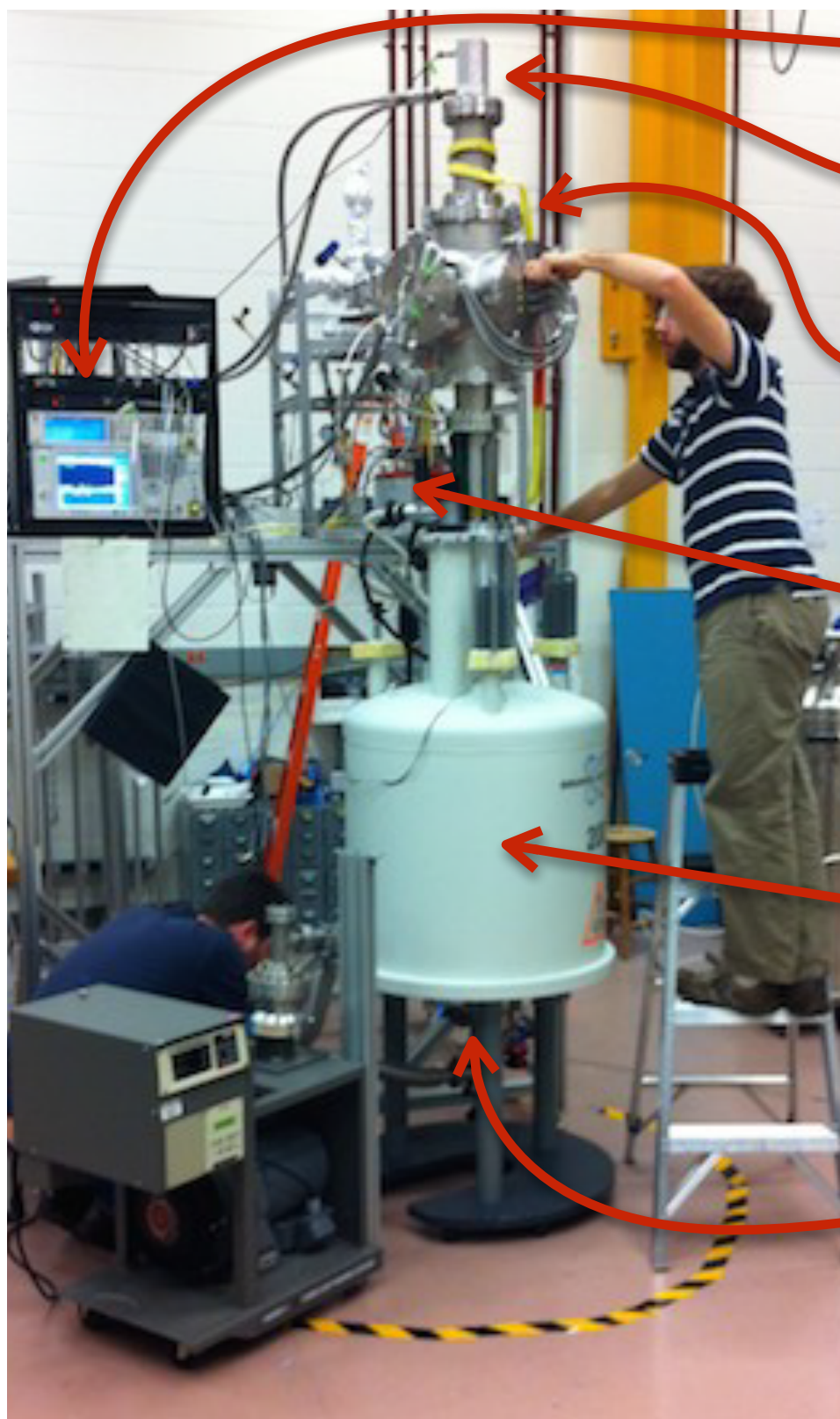
many overlapping
low-energy electrons



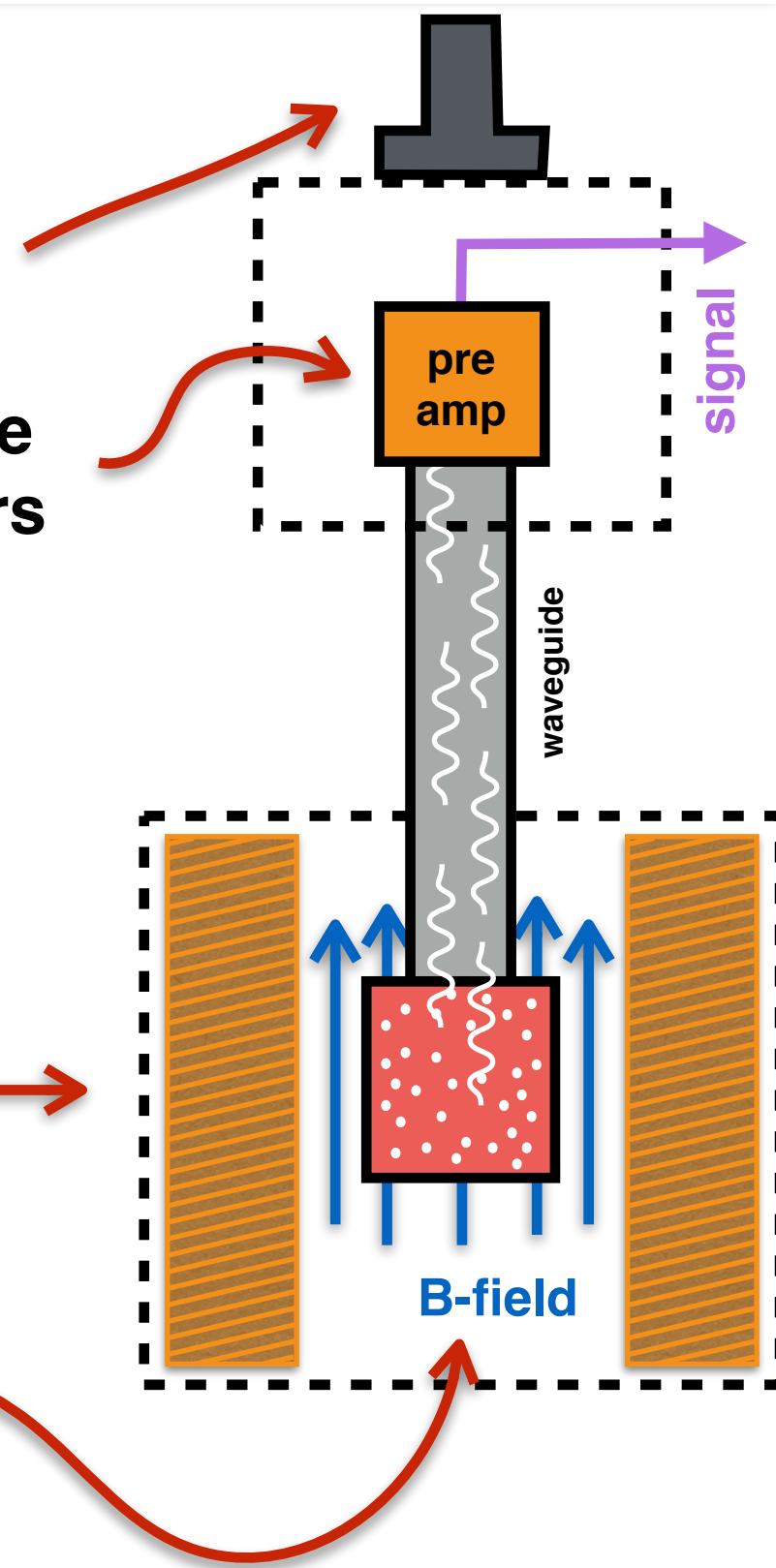
BM & Formaggio, PhysRevD 2009

100,000 simulated T_2 decays

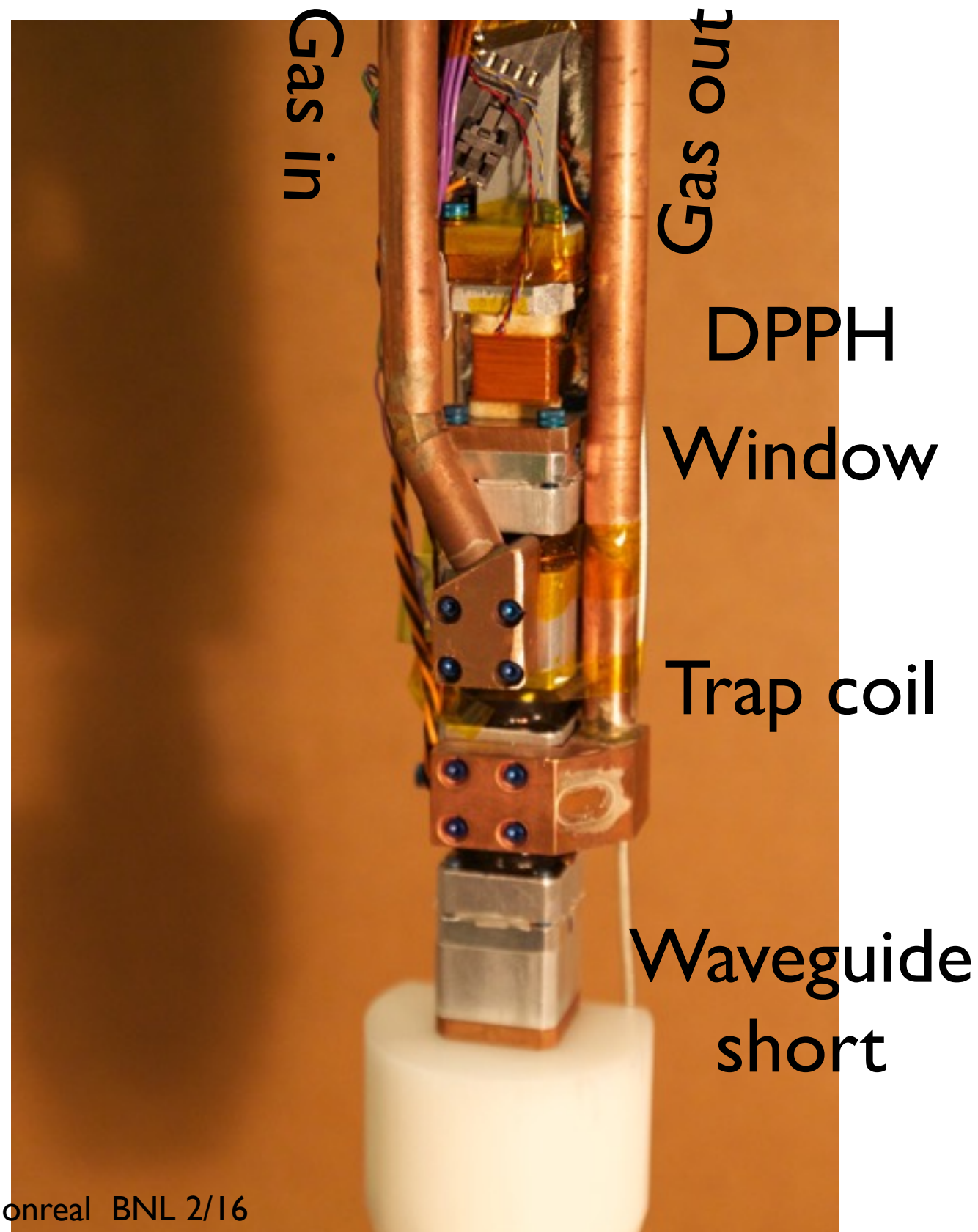




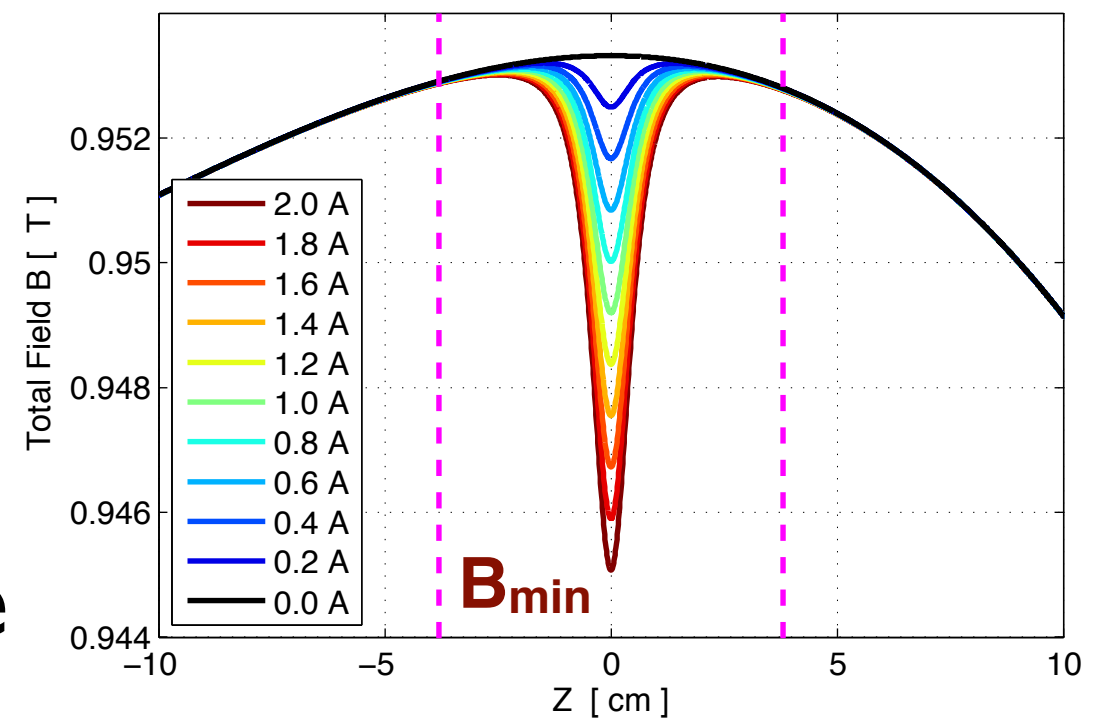
- Receiver
- 50 K cold head
- Cryogenic low-noise microwave amplifiers
- ^{83}mKr gas system
- superconducting magnet ~ 1 T, 52 mm warm bore
- Insert Gas Cell + Waveguide (inside)



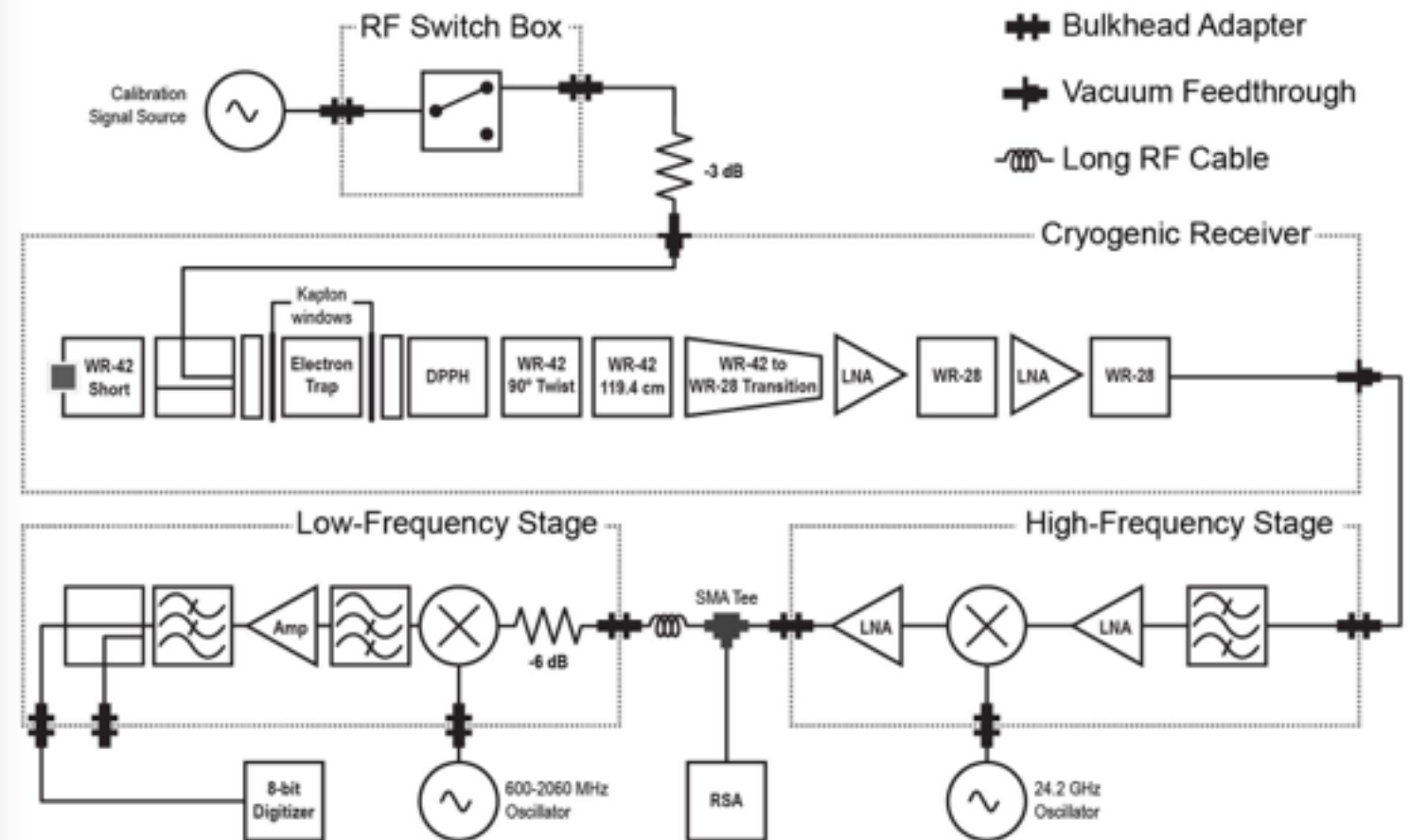
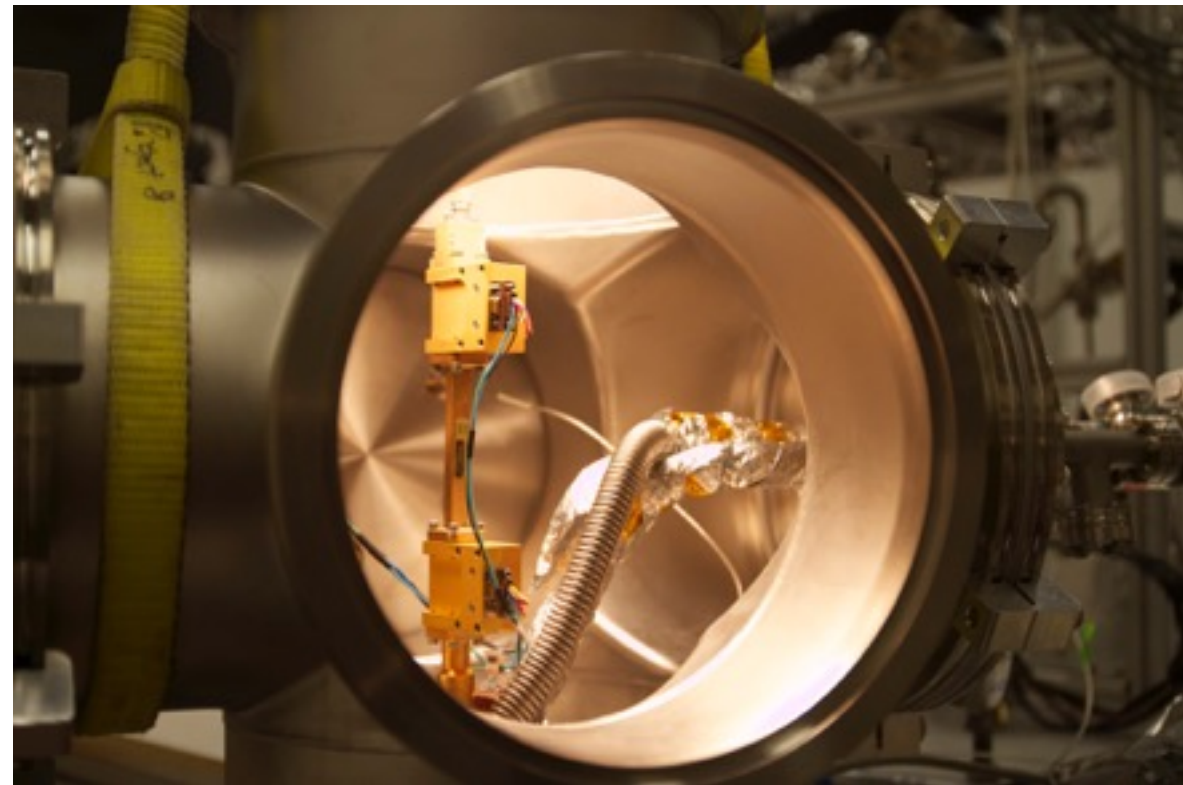
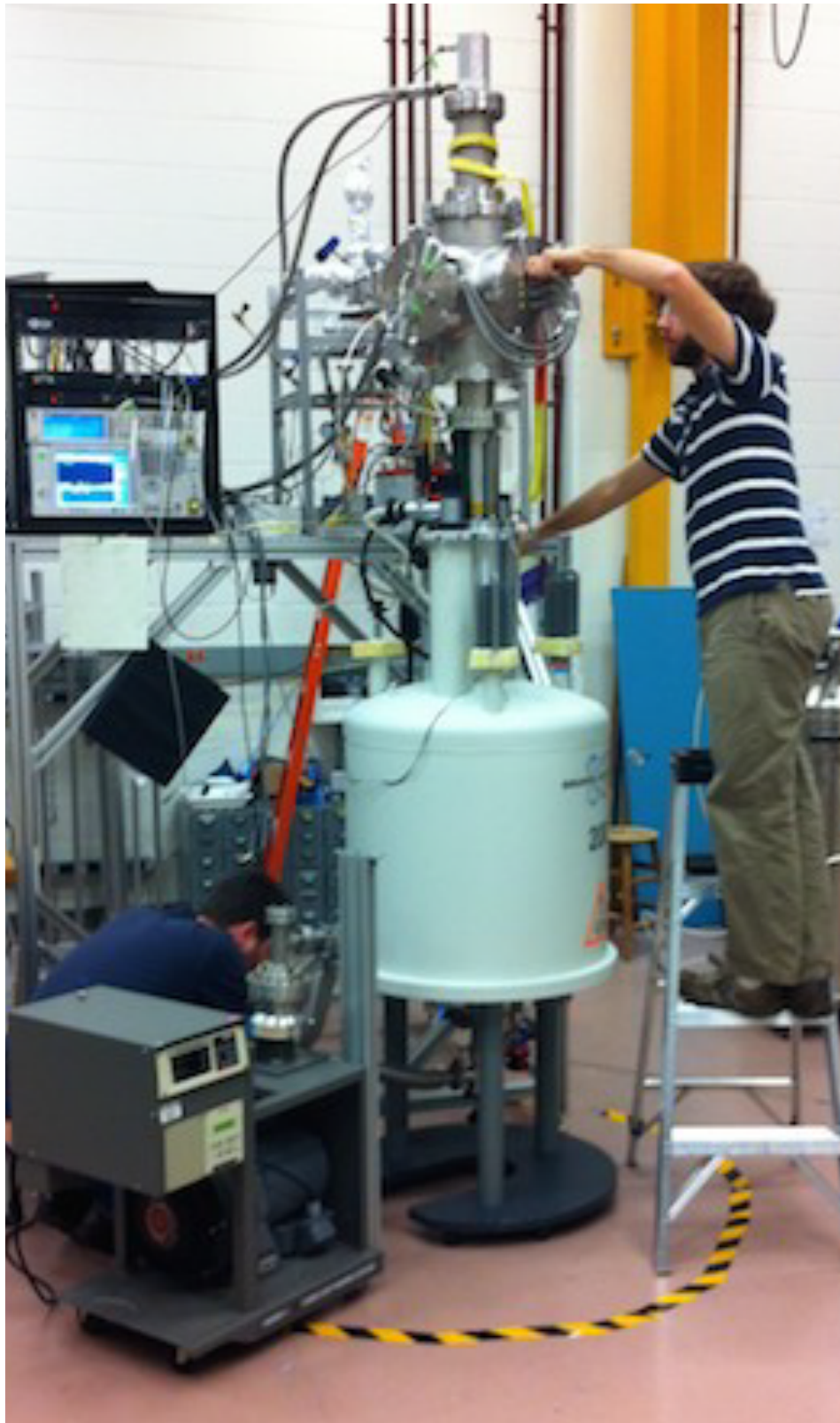
Waveguide cell

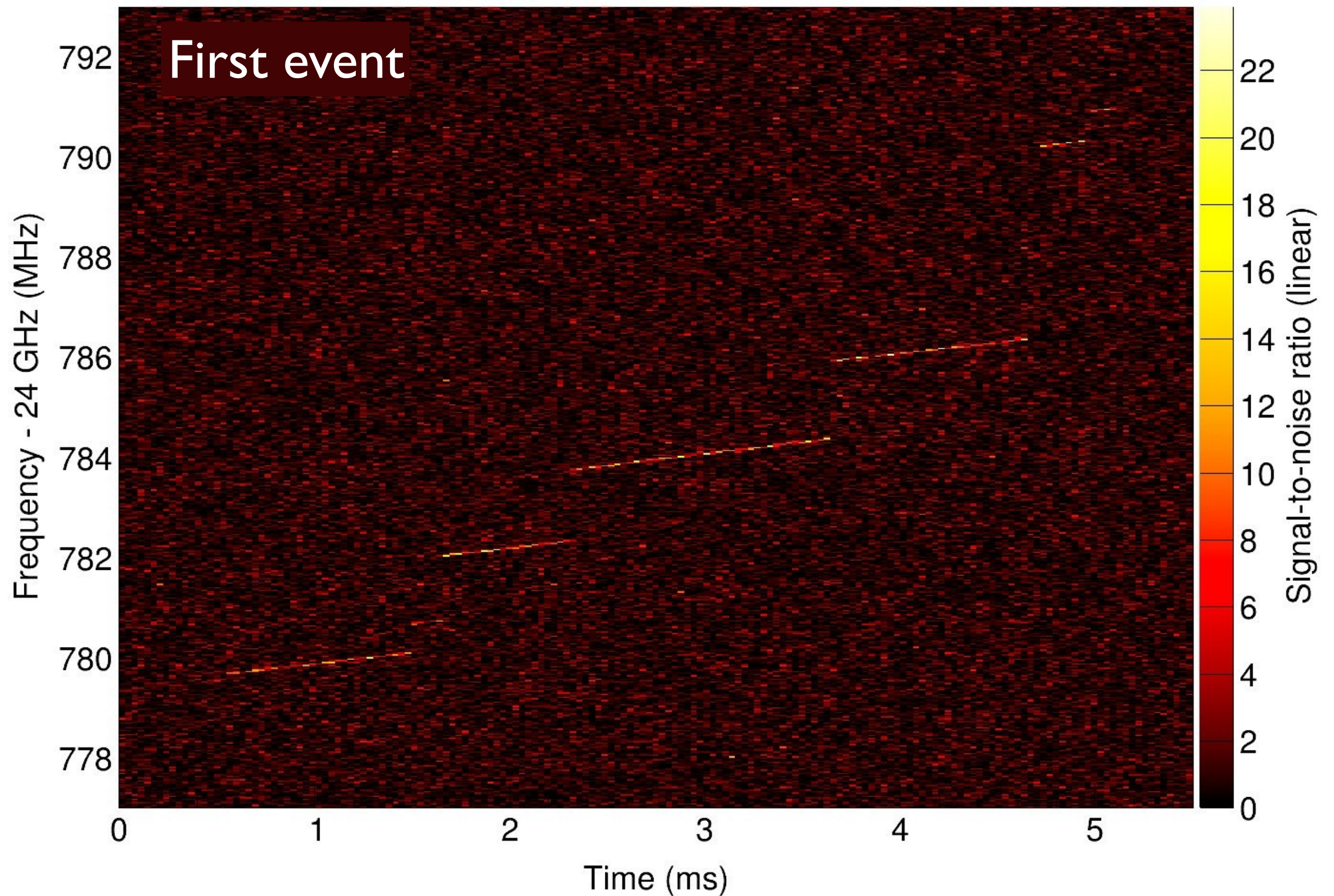


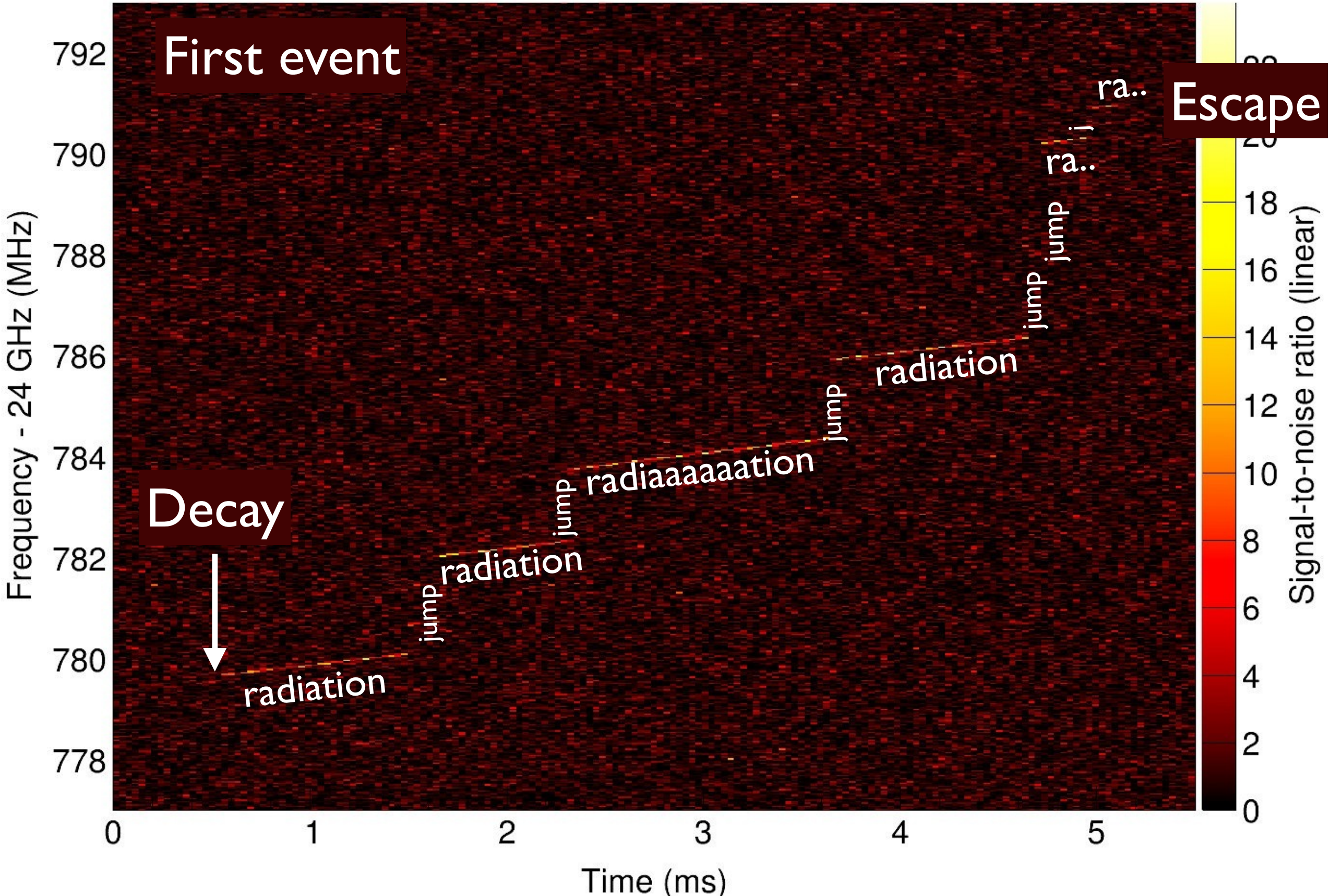
Gas = $^{83\text{m}}\text{Kr}$
1.8 hour decay
Monoenergetic e^- lines
at 17.8, 30, 32 keV



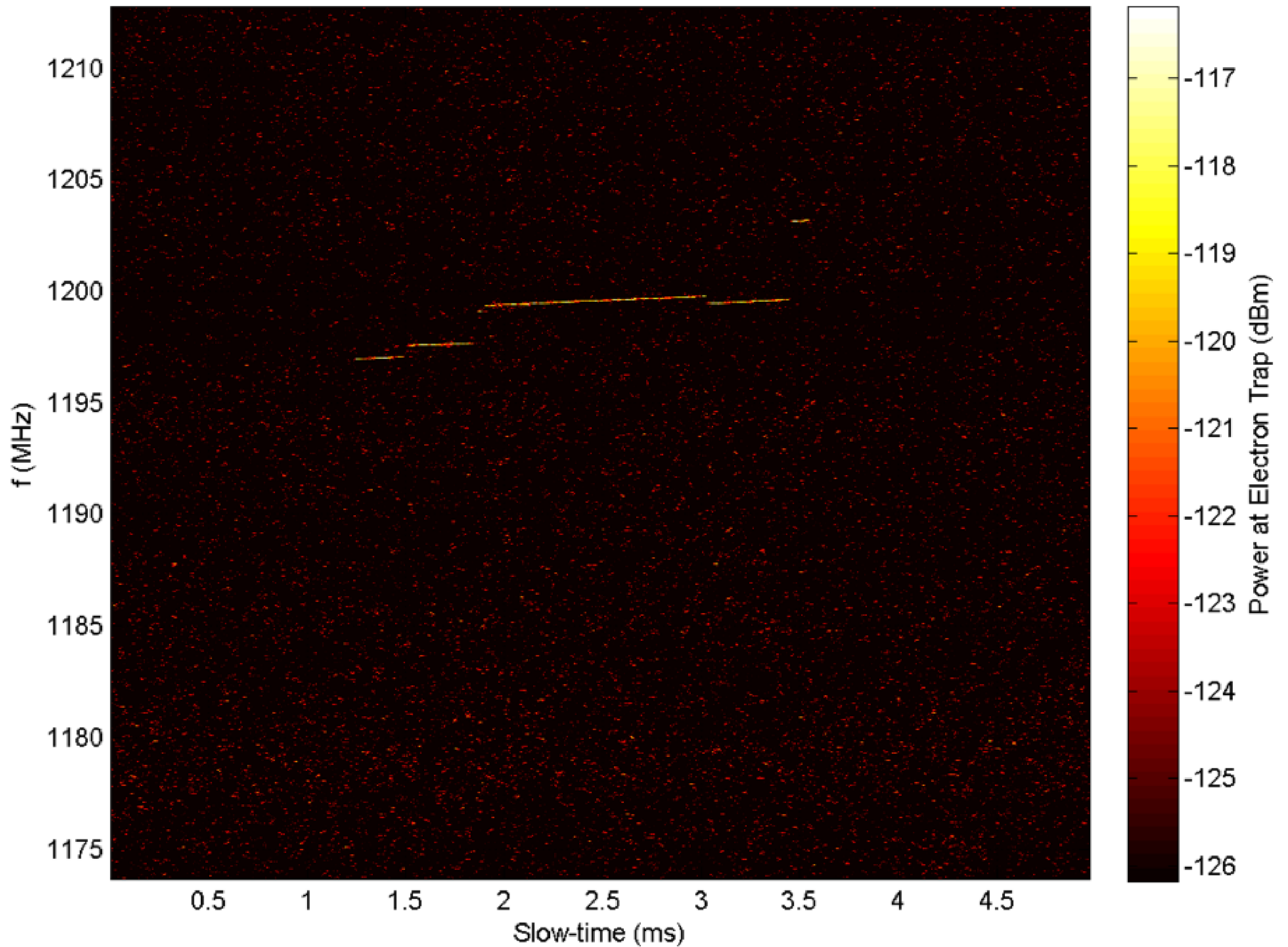
RF chain and receiver



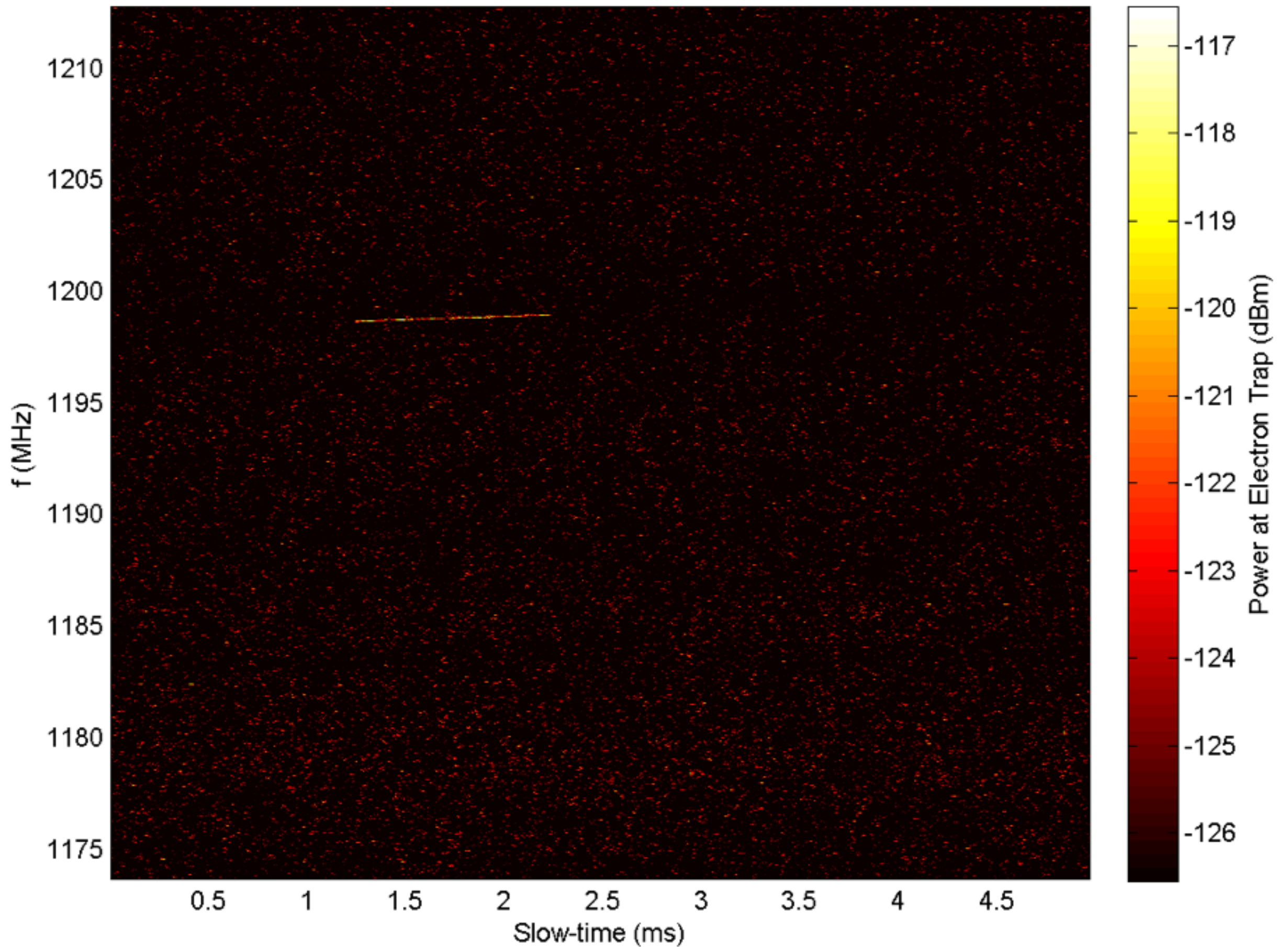




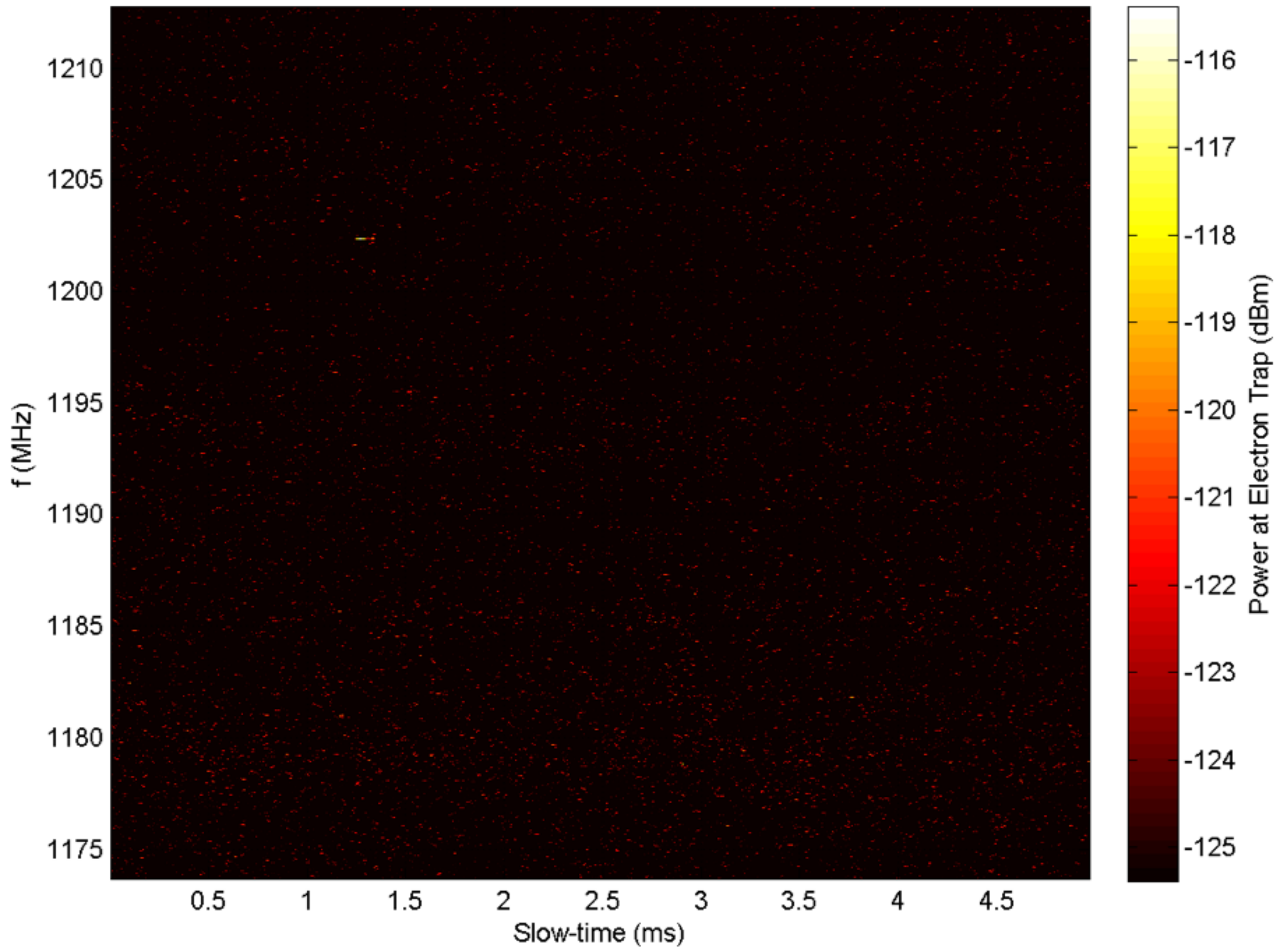
Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.14.58.02.664.MAT



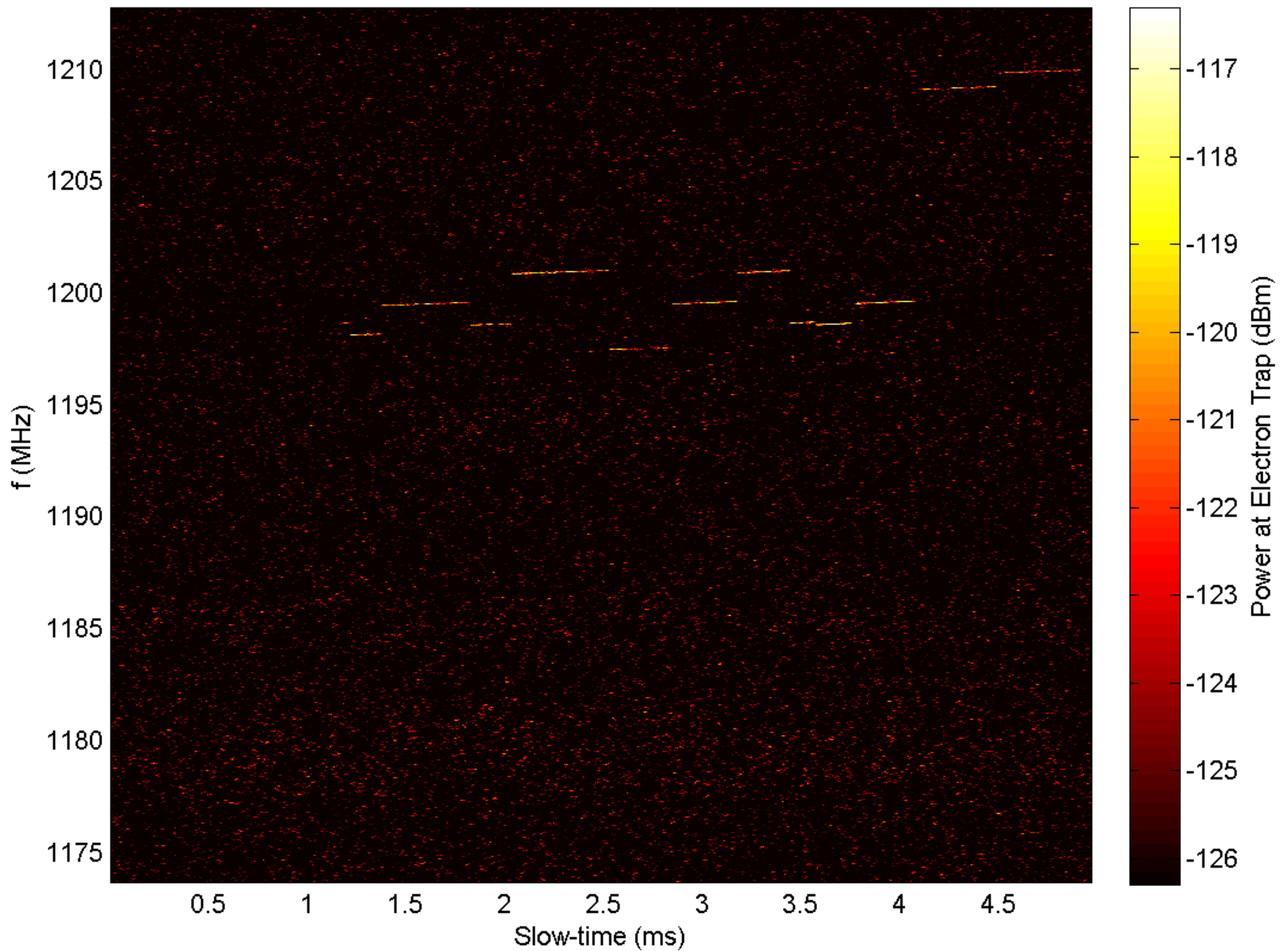
Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.14.56.32.668.MAT



Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.14.57.47.031.MAT



Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.14.57.05.816.MAT



Fall 1997

K-E 10 X 10 TO THE CENTIN
KEUFFEL & ESSER CO. MAD

lab partner's handwriting

46 1510

Figure 2

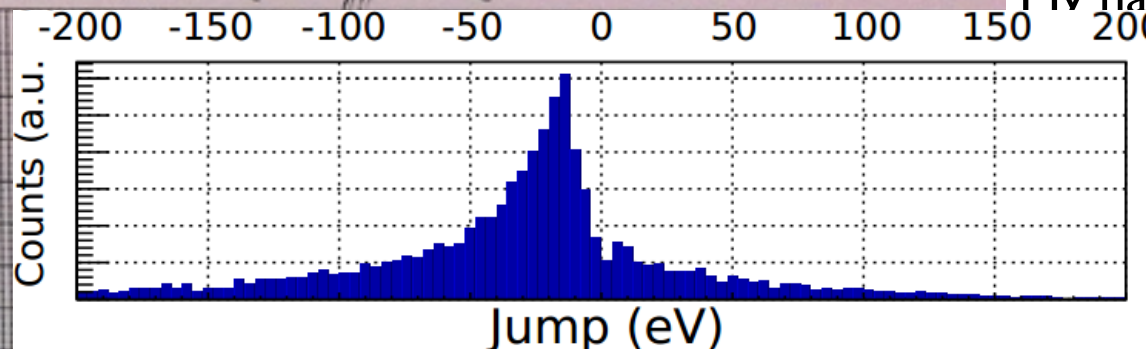
Gridlat 1.3 V

Grid Z sweeping 0 - 31 V

Filament at 6.4 V

Peak Resolution at Different T

Mv handwriting



←4.9V→ ←4.9V→ ←4.9V→

Conclusion: electrons
lose ~4.9 V in each atomic
collision

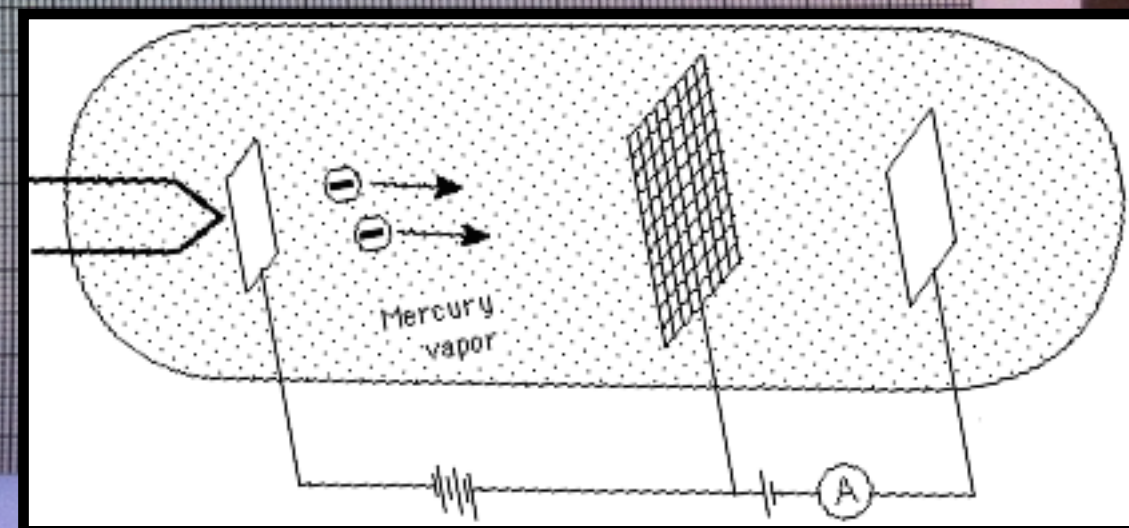
~~Handwritten notes:~~
 $Y = 50 \text{ mV/cm}$
 $X = 2 \text{ V/cm}$

current

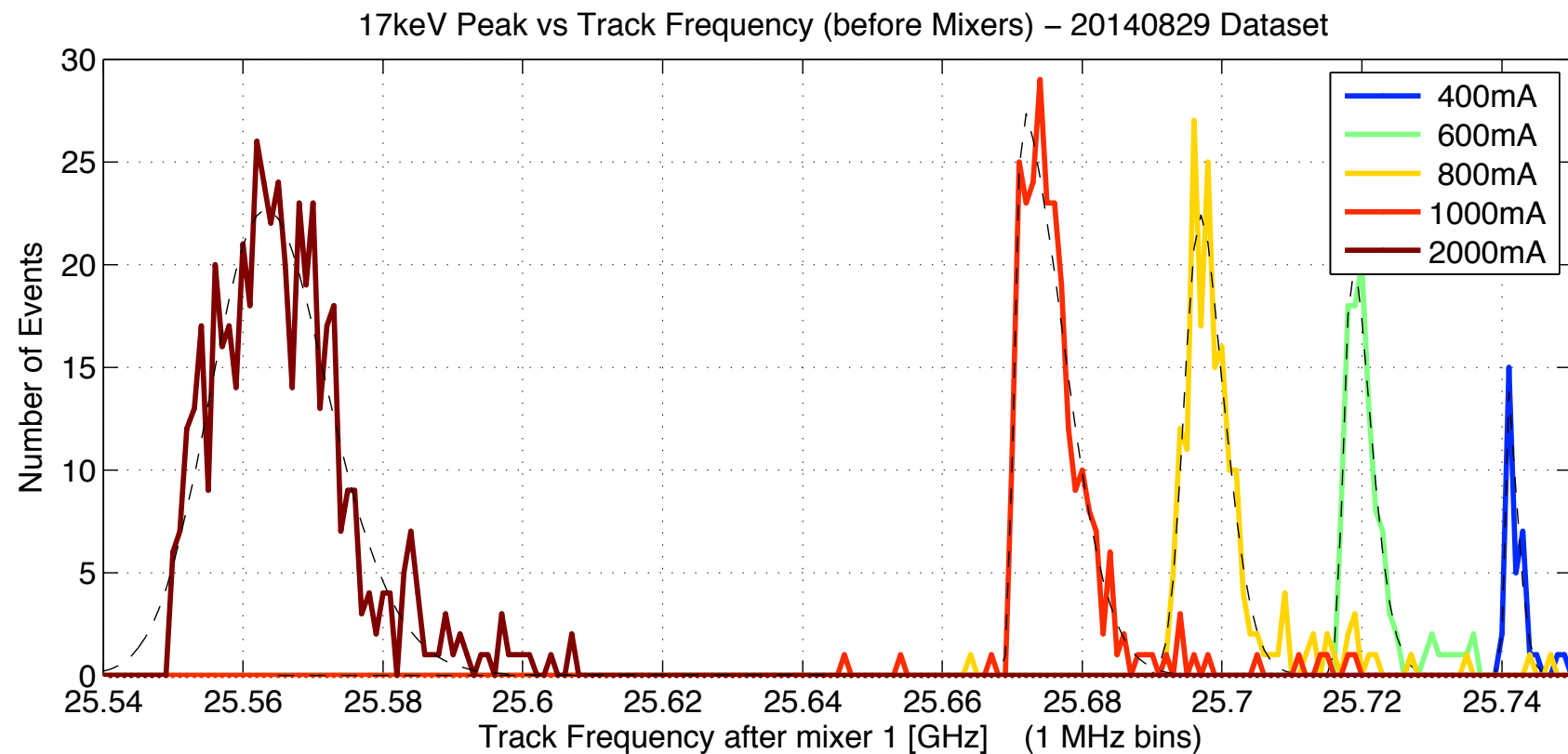
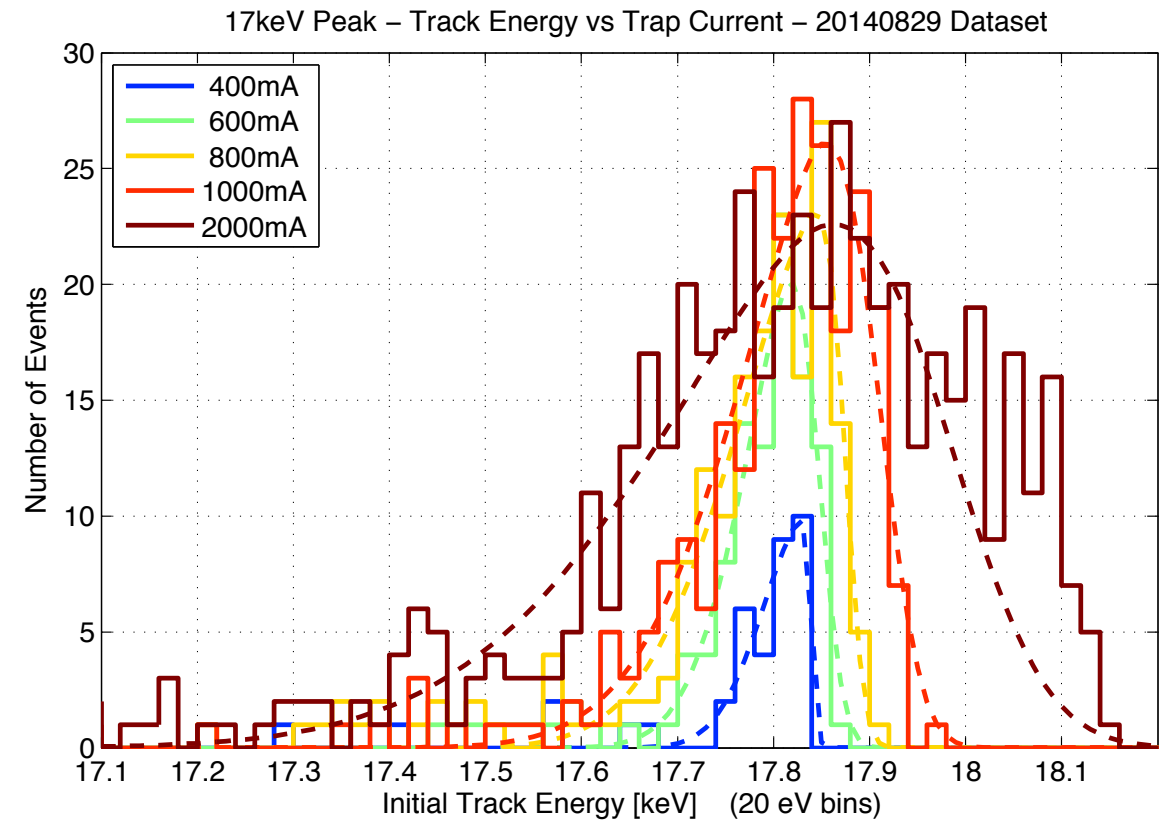
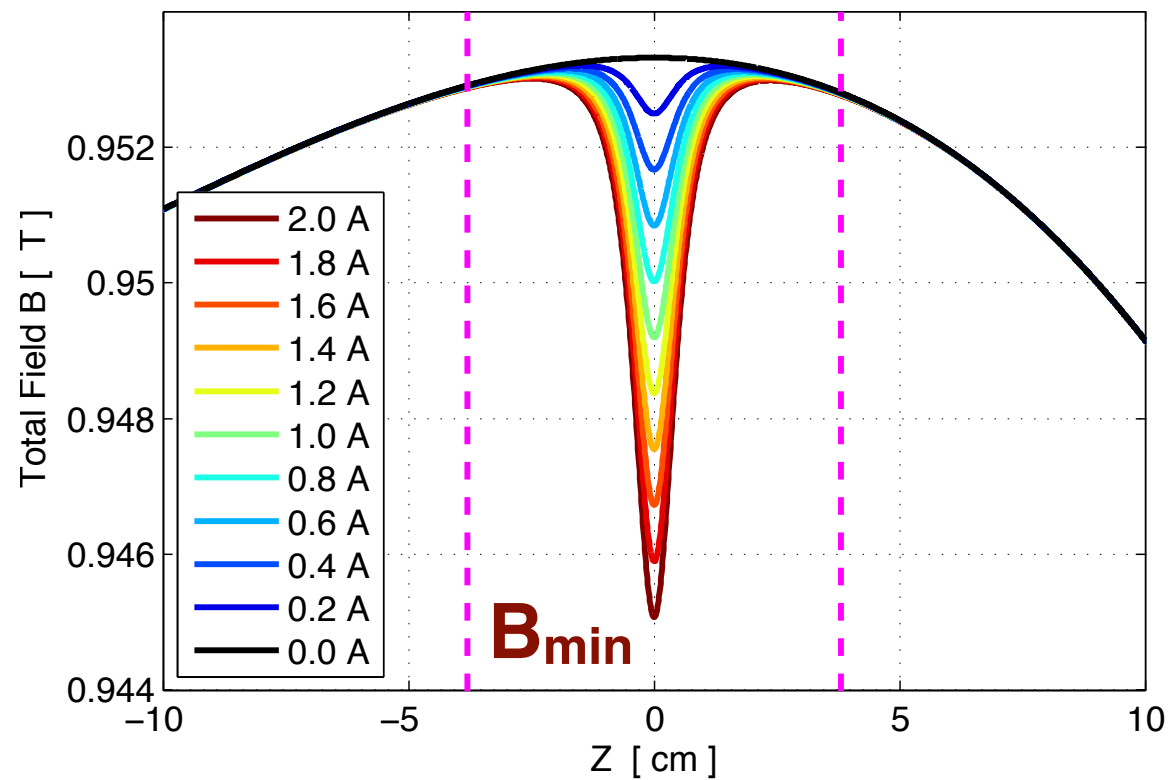
↑
current

It's the Frank-Hertz experiment!

electron accelerating voltage →

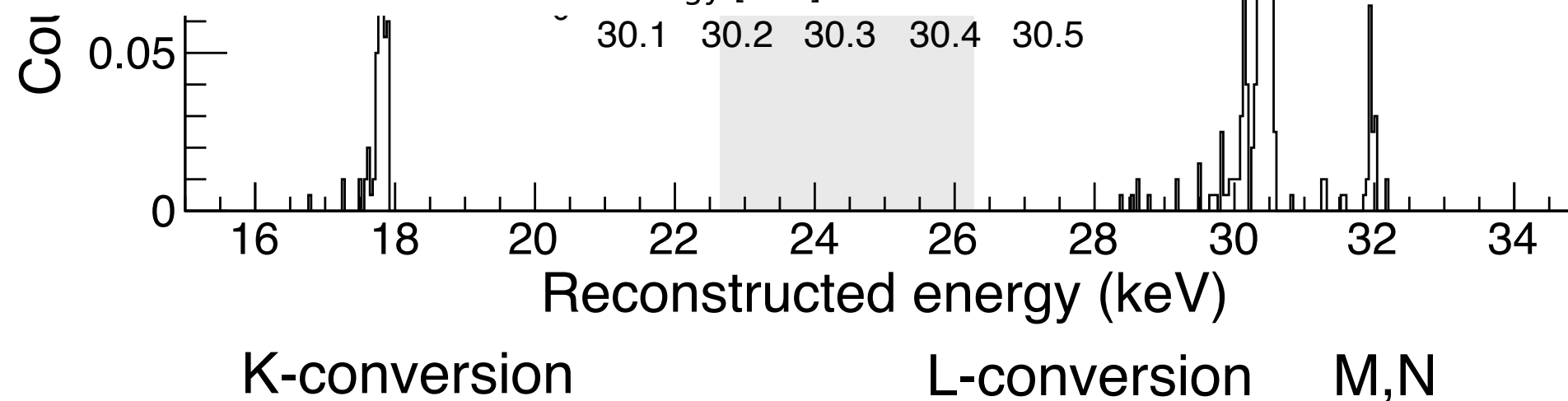
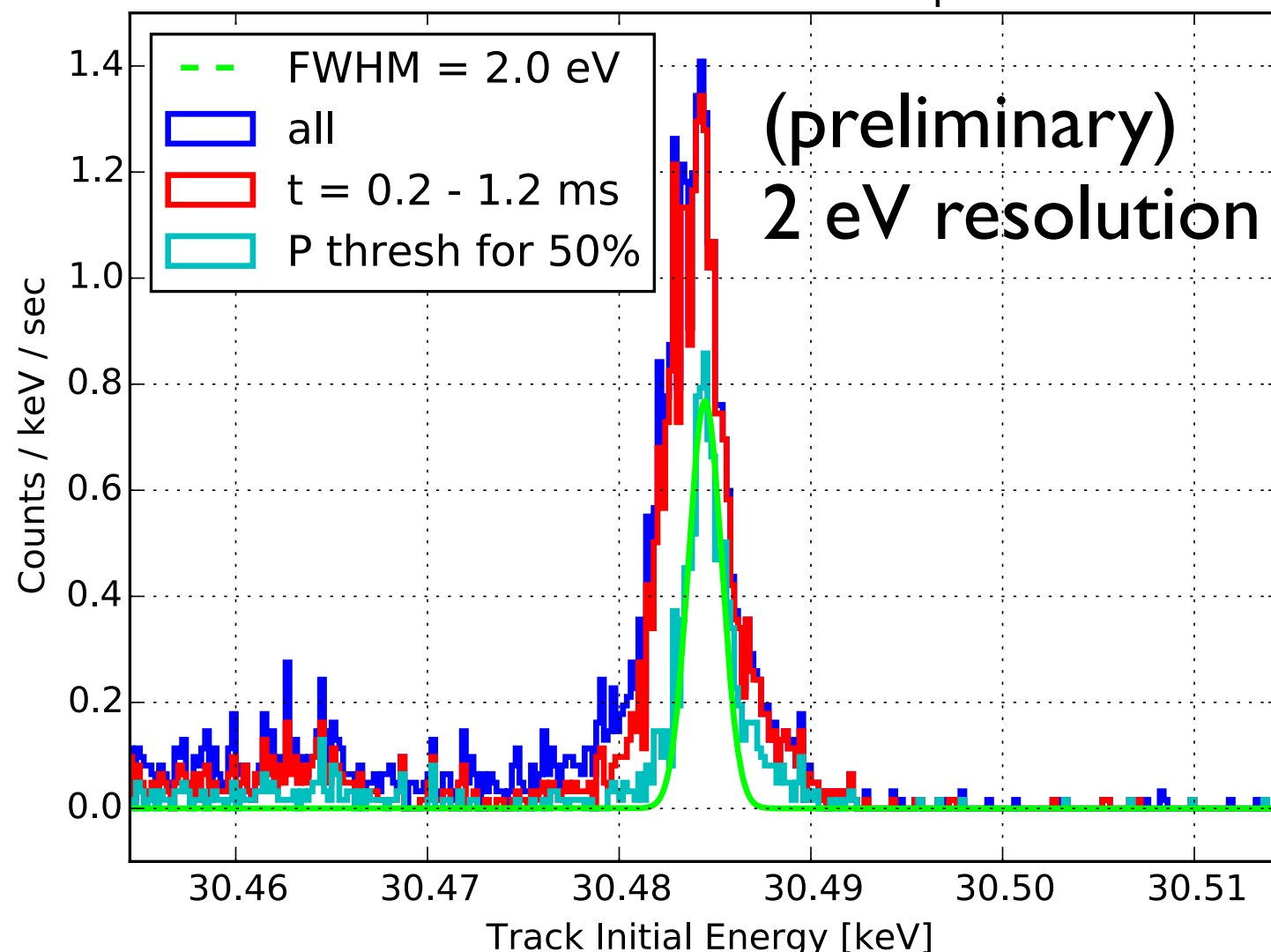


Magnetic trap is a B field nonuniformity

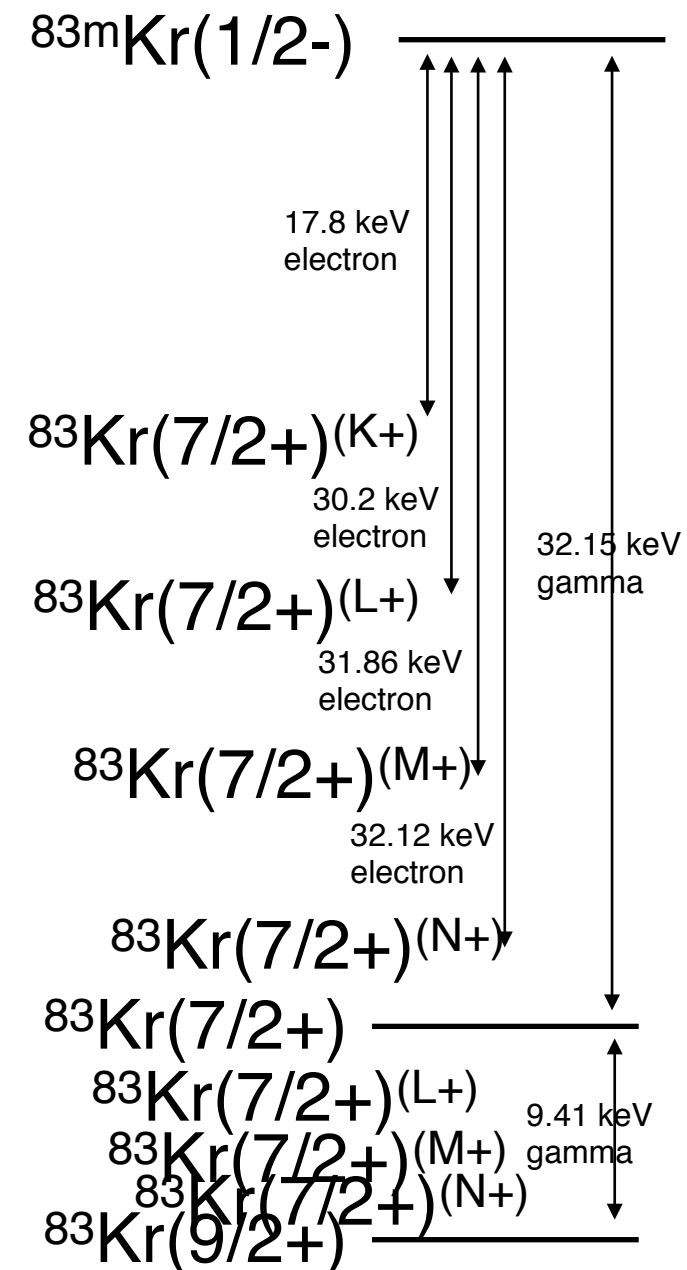


spectrum

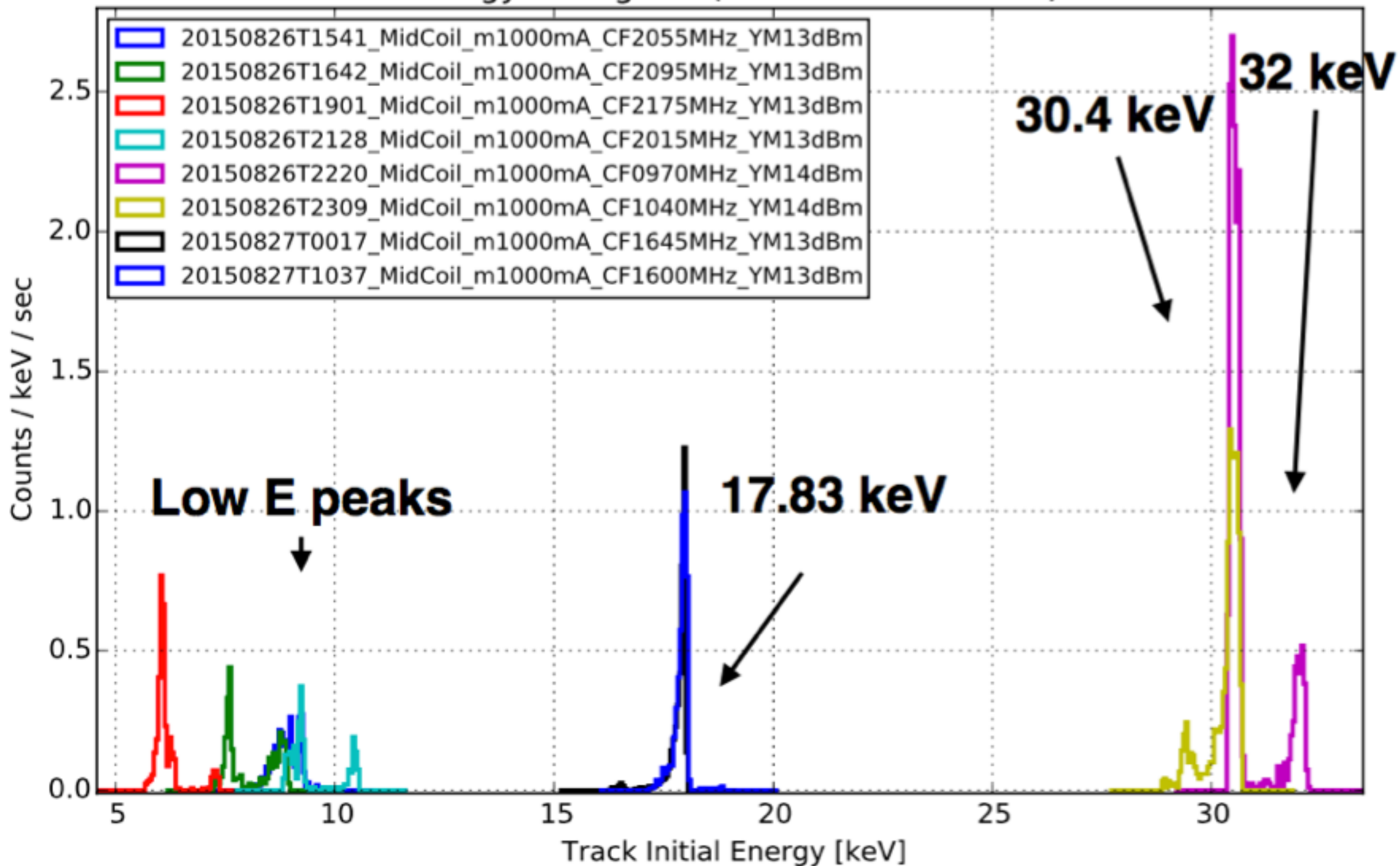
Energy Histogram (bin width = 0.2 eV) (10269 acqs)
 20150227 FullBathTubTrapAt1A



(published) 15 eV resolution!

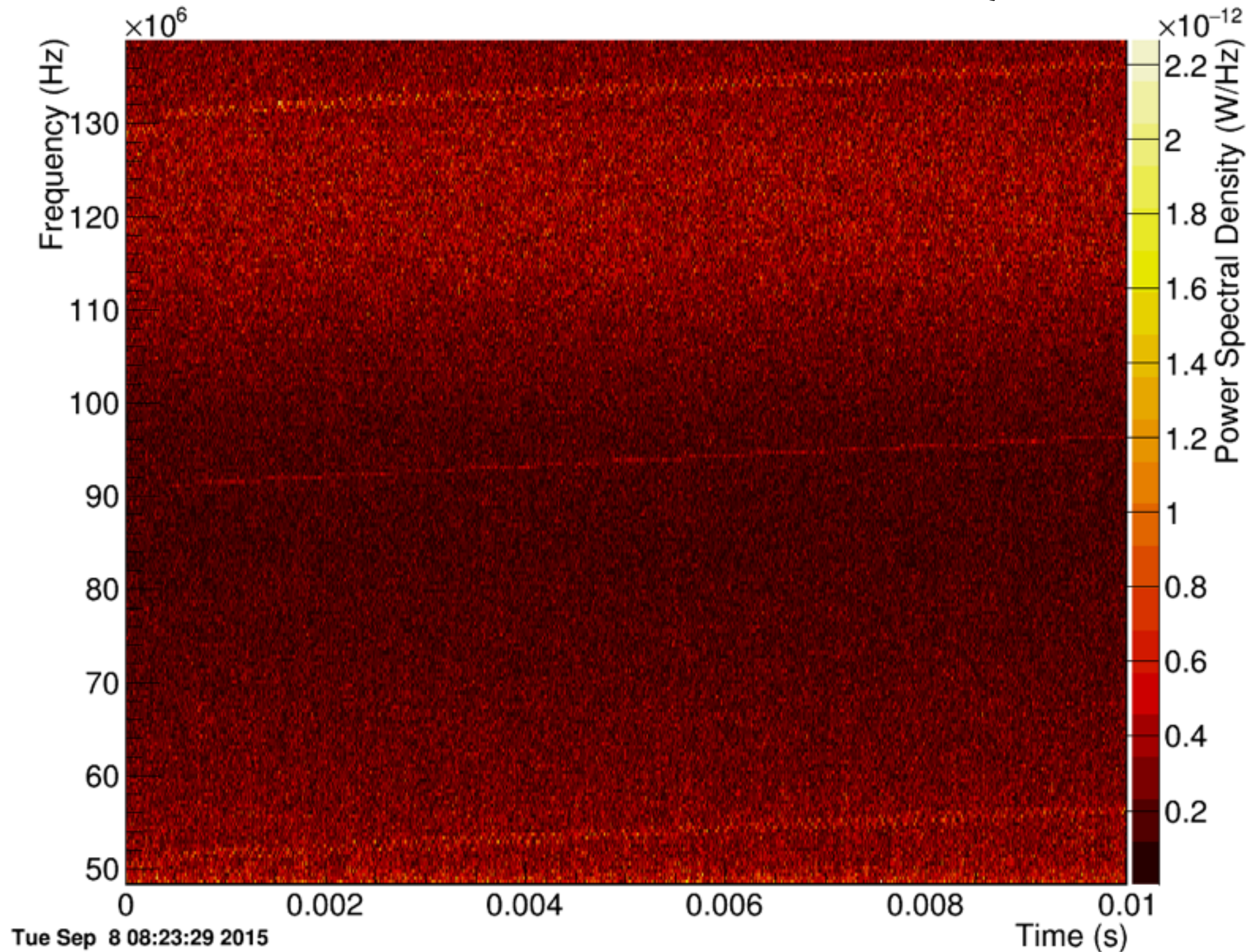


Energy Histogram (bin width = 50.0 eV)

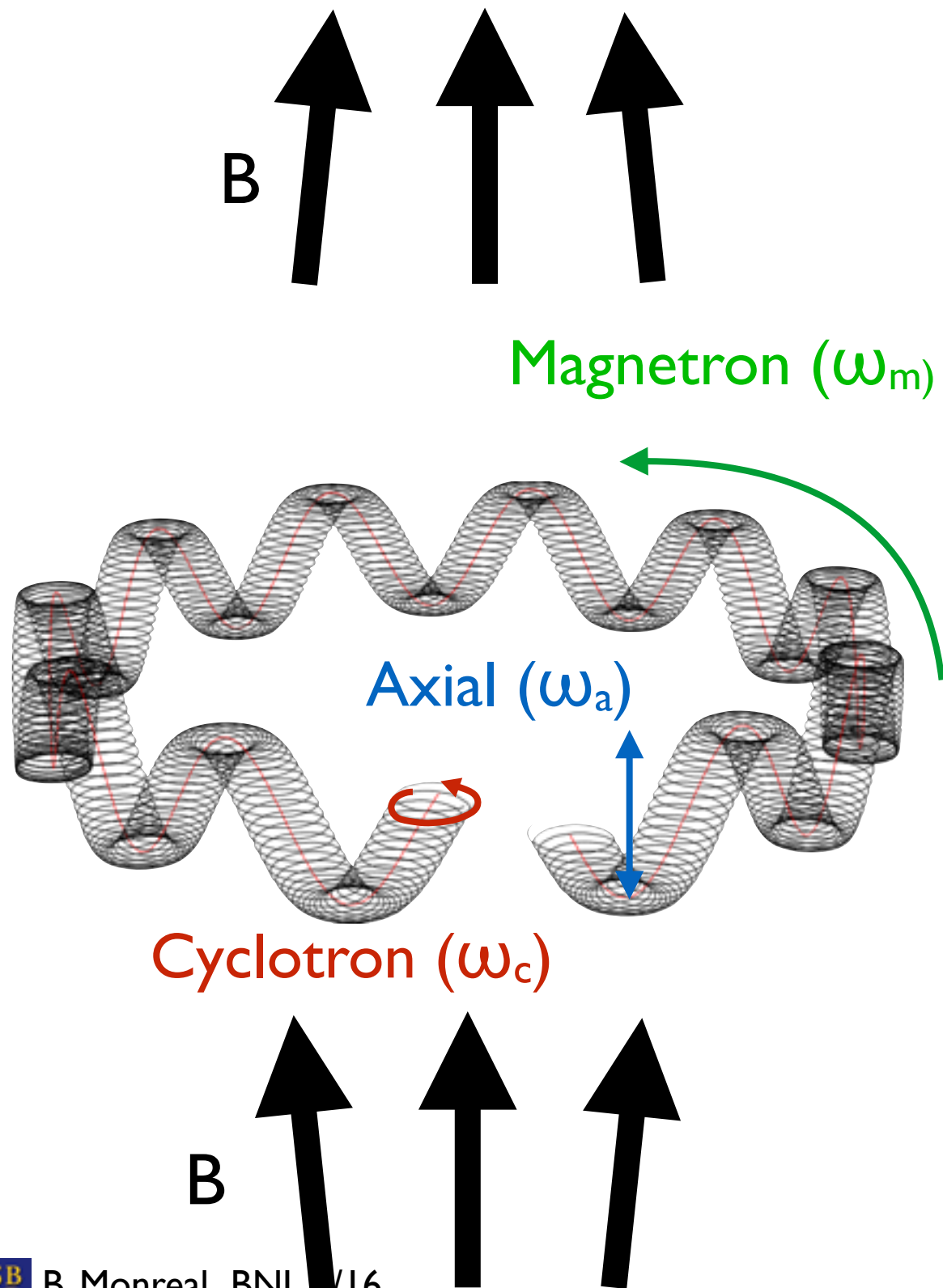


Run 2: knocking down the noise

Cold head rebuild
Tighten screws (!)
new DAQ



Doppler shifts and nonuniformities



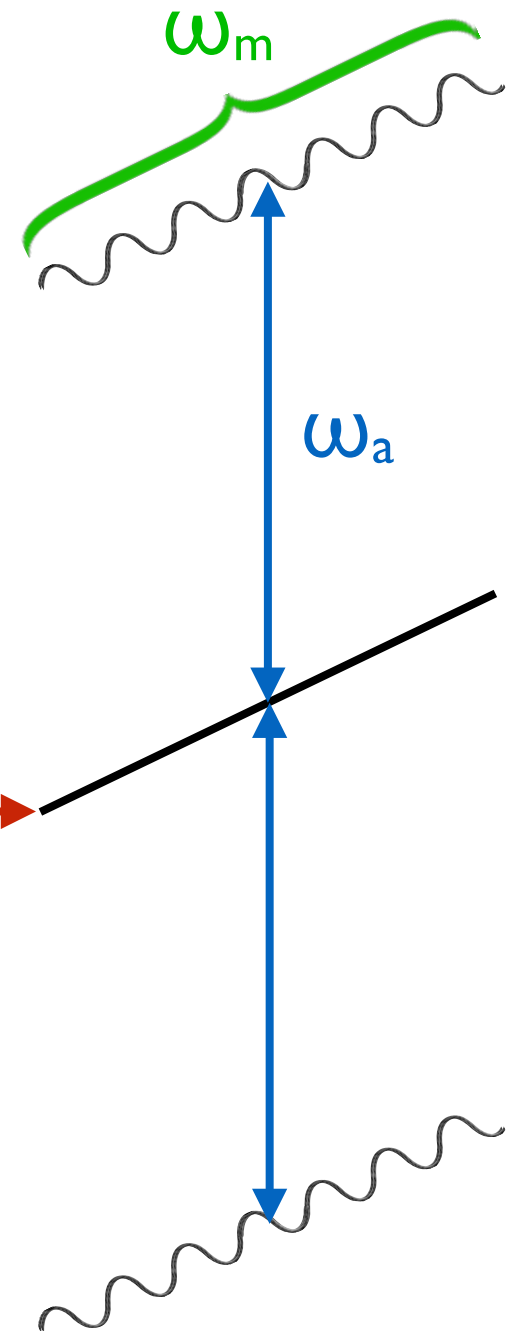
10 kHz

50 MHz

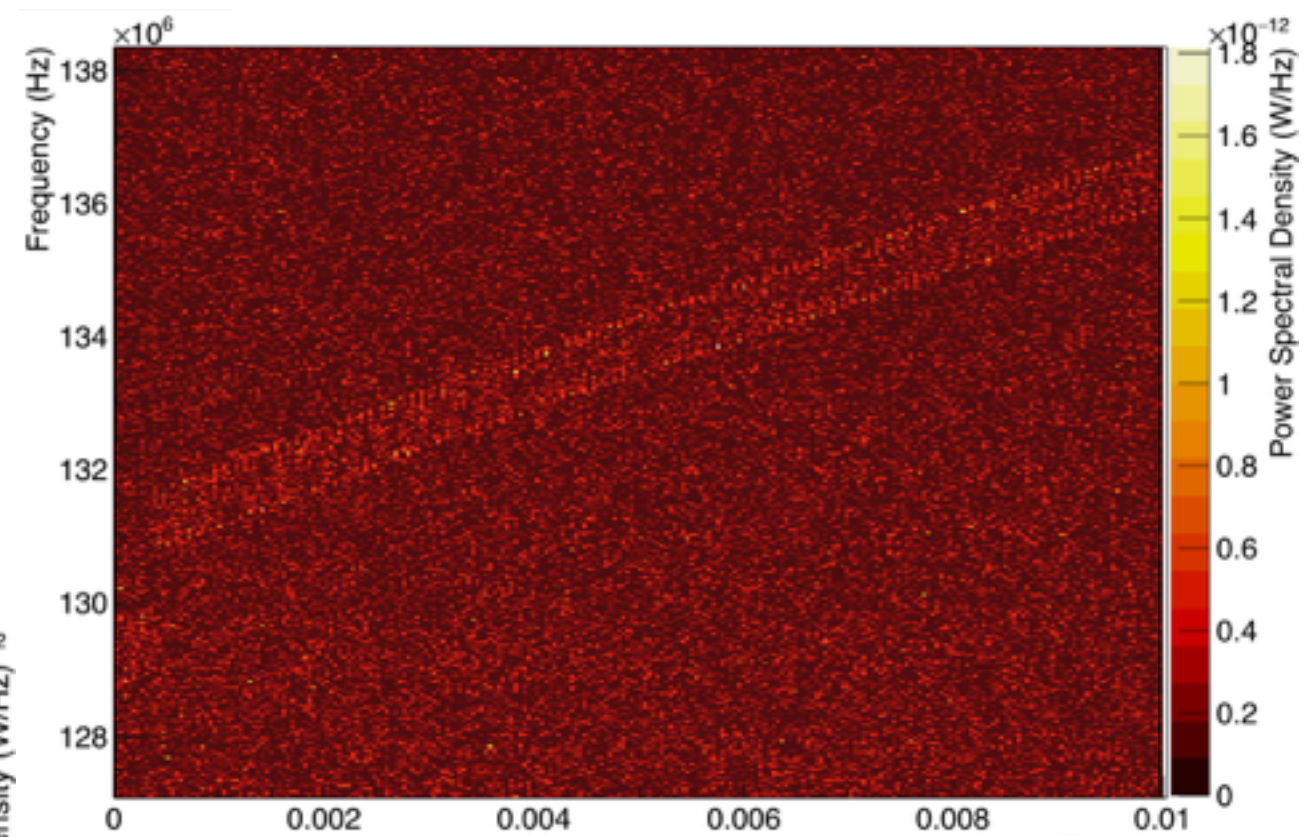
26 GHz

50 MHz

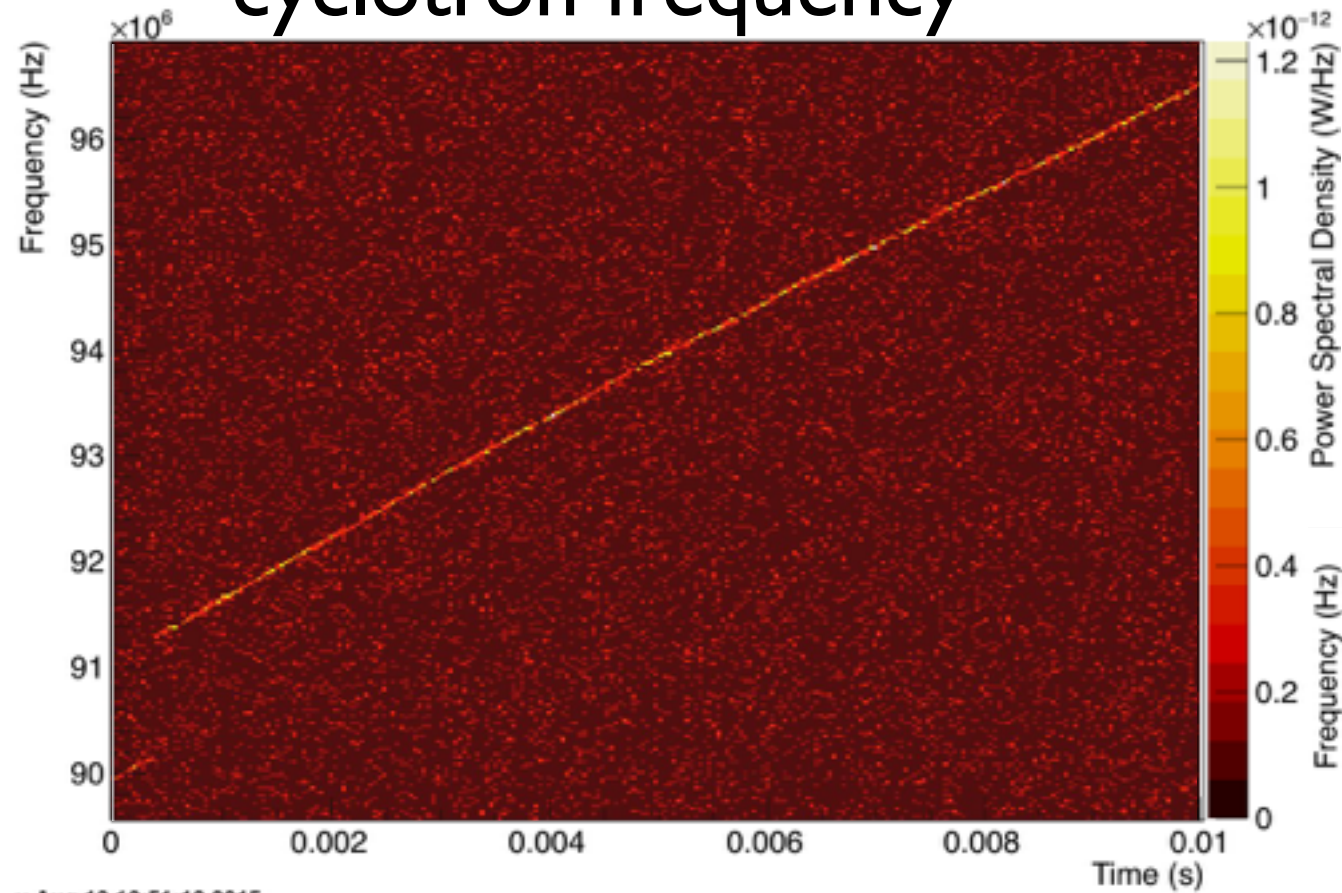
10 kHz



upper sideband

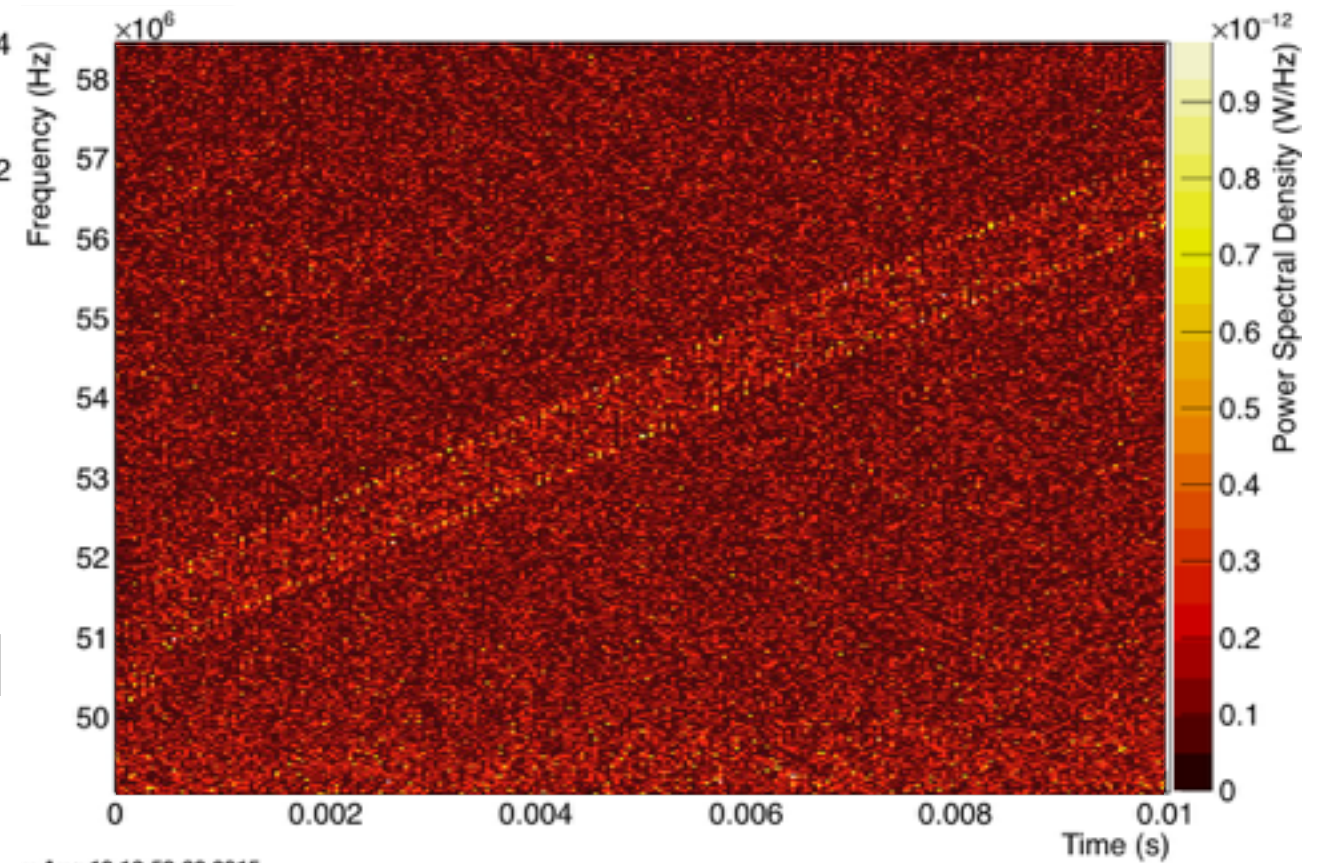


cyclotron frequency

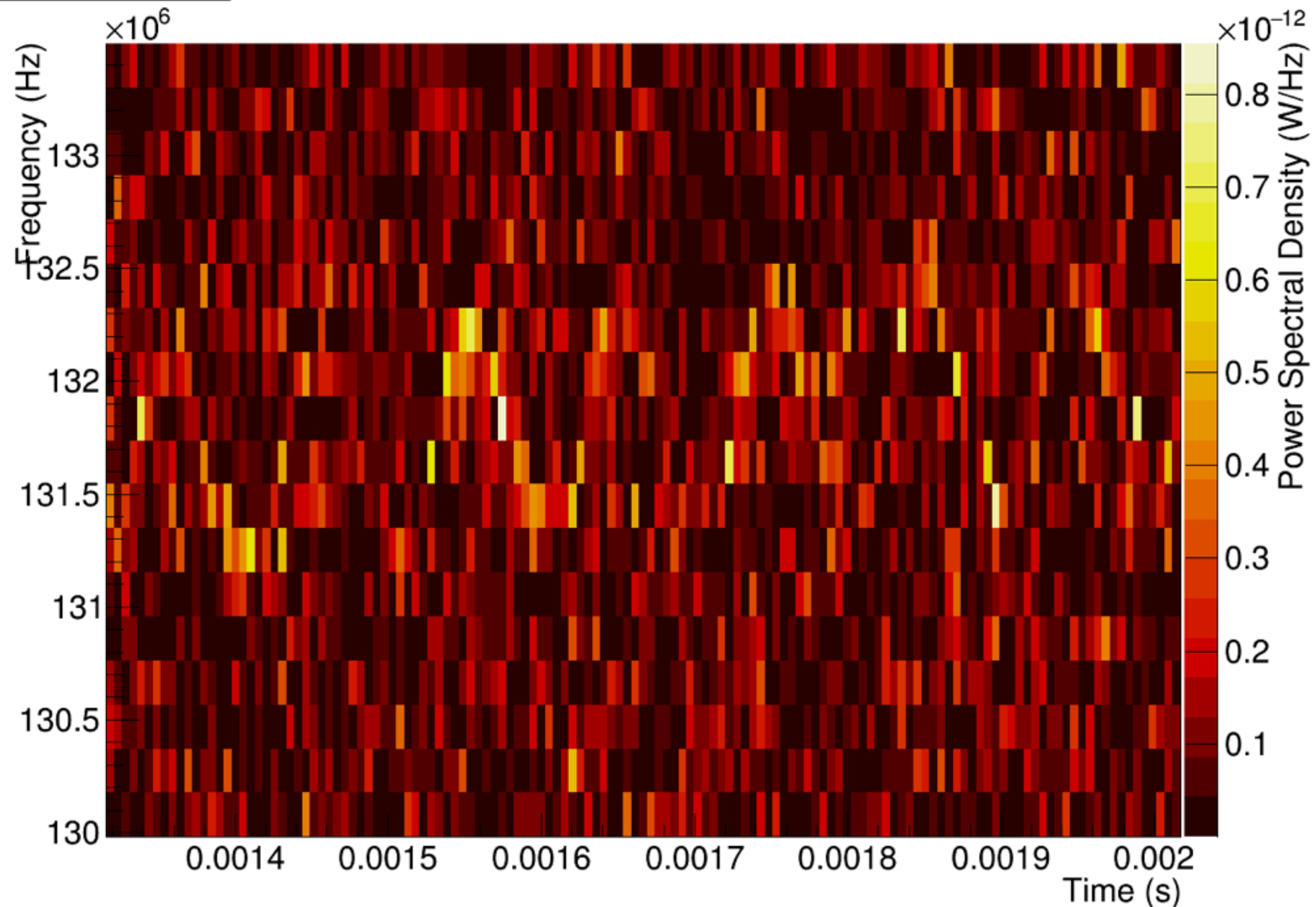


± 40 MHz

lower sideband



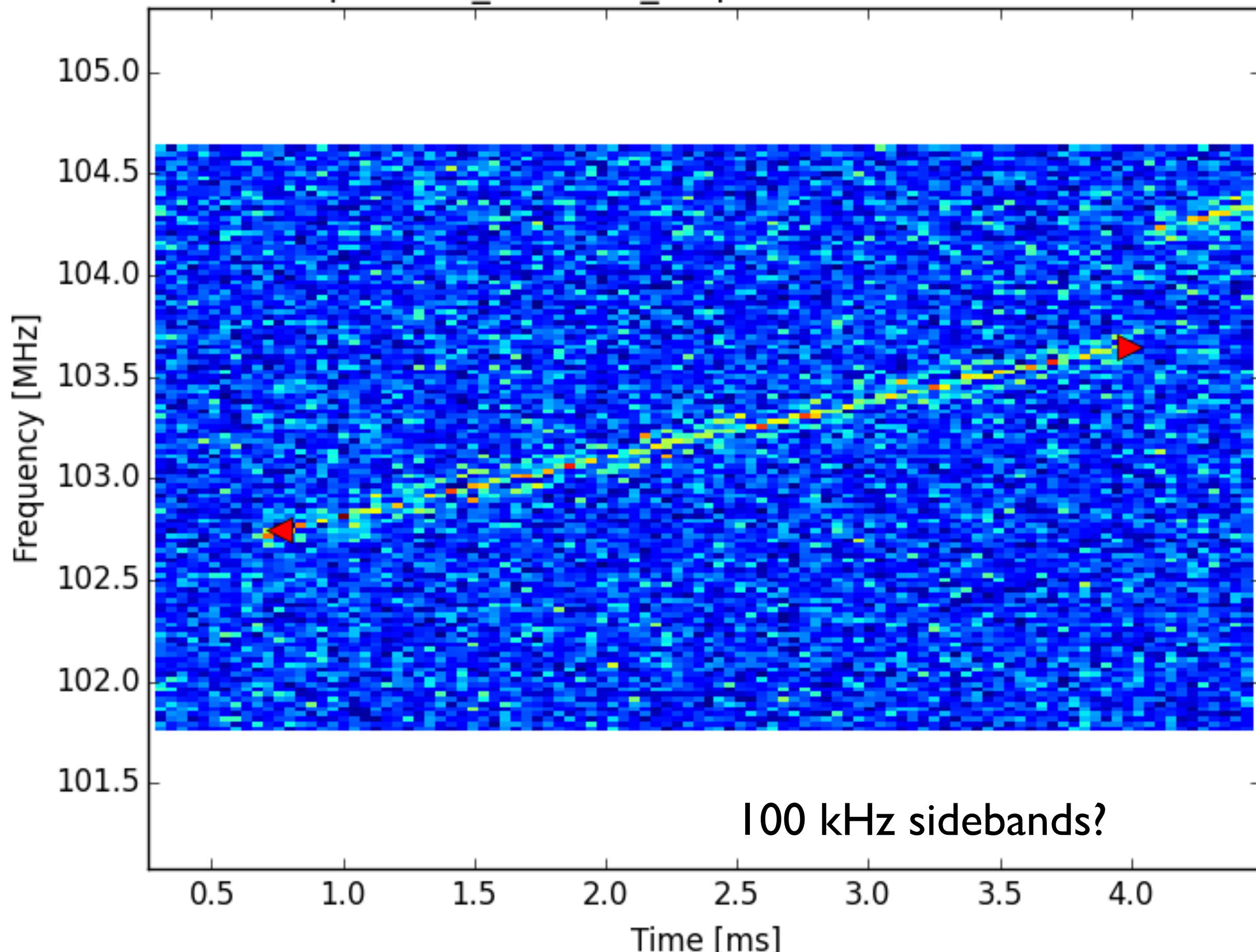
Spectrogram

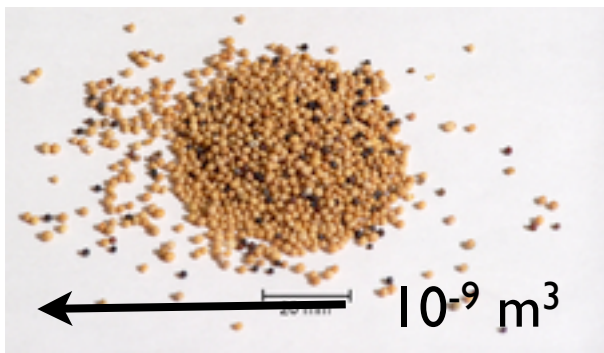


Mon Aug 17 14:47:00 2015

10 kHz frequency modulation

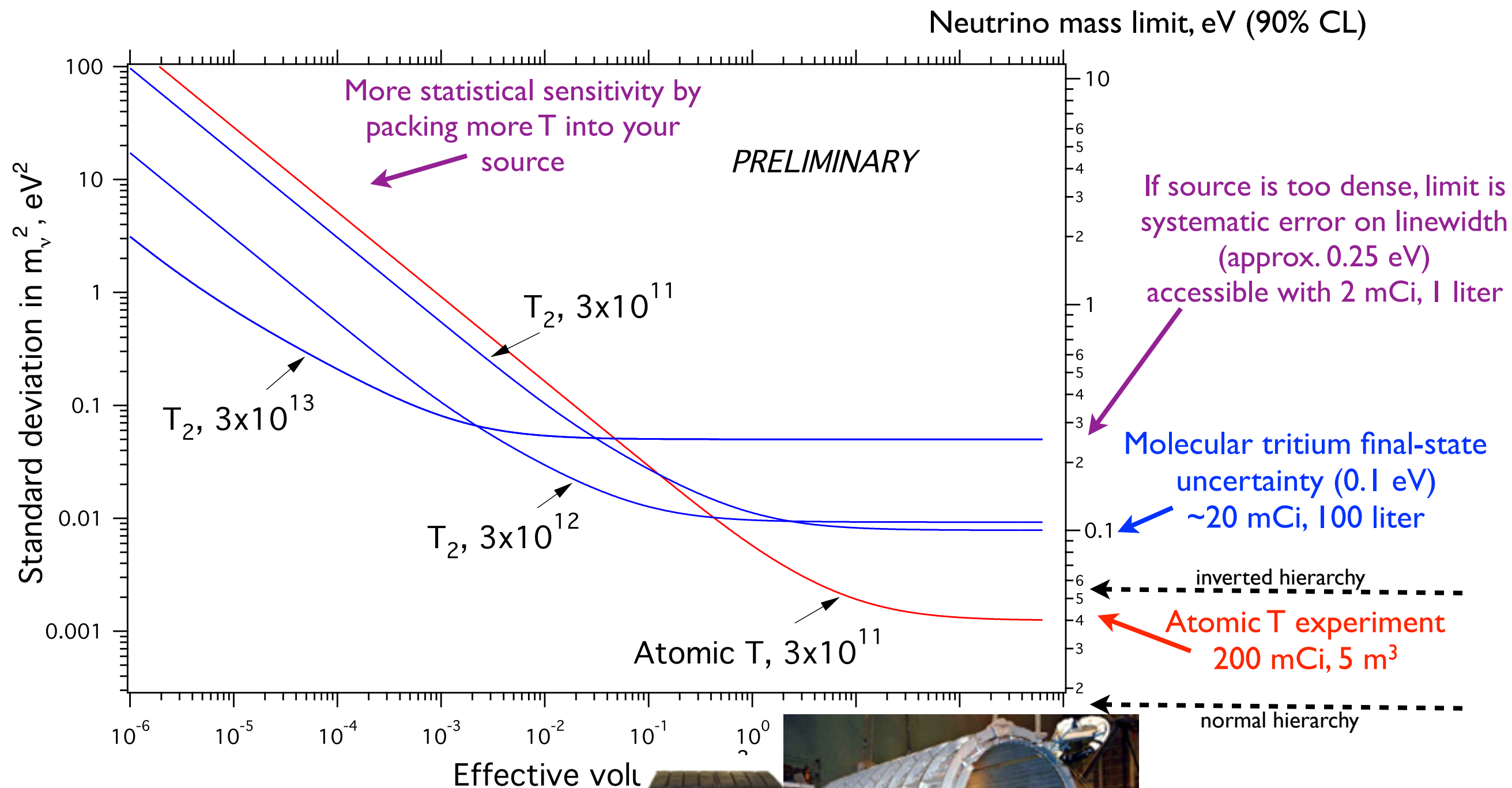
AcqID=1, ii_file=0, ii_AcqInFile=1, EventIDs = 2



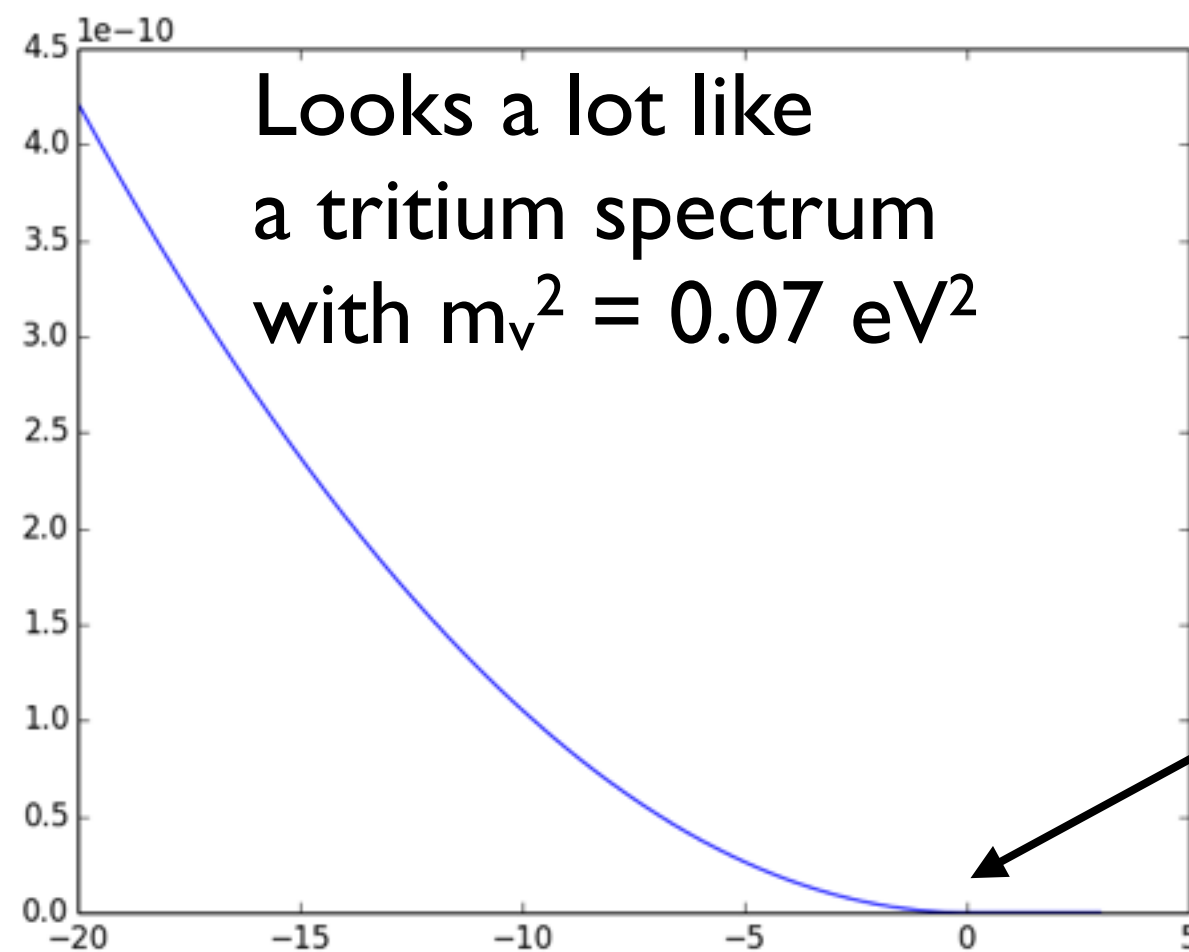
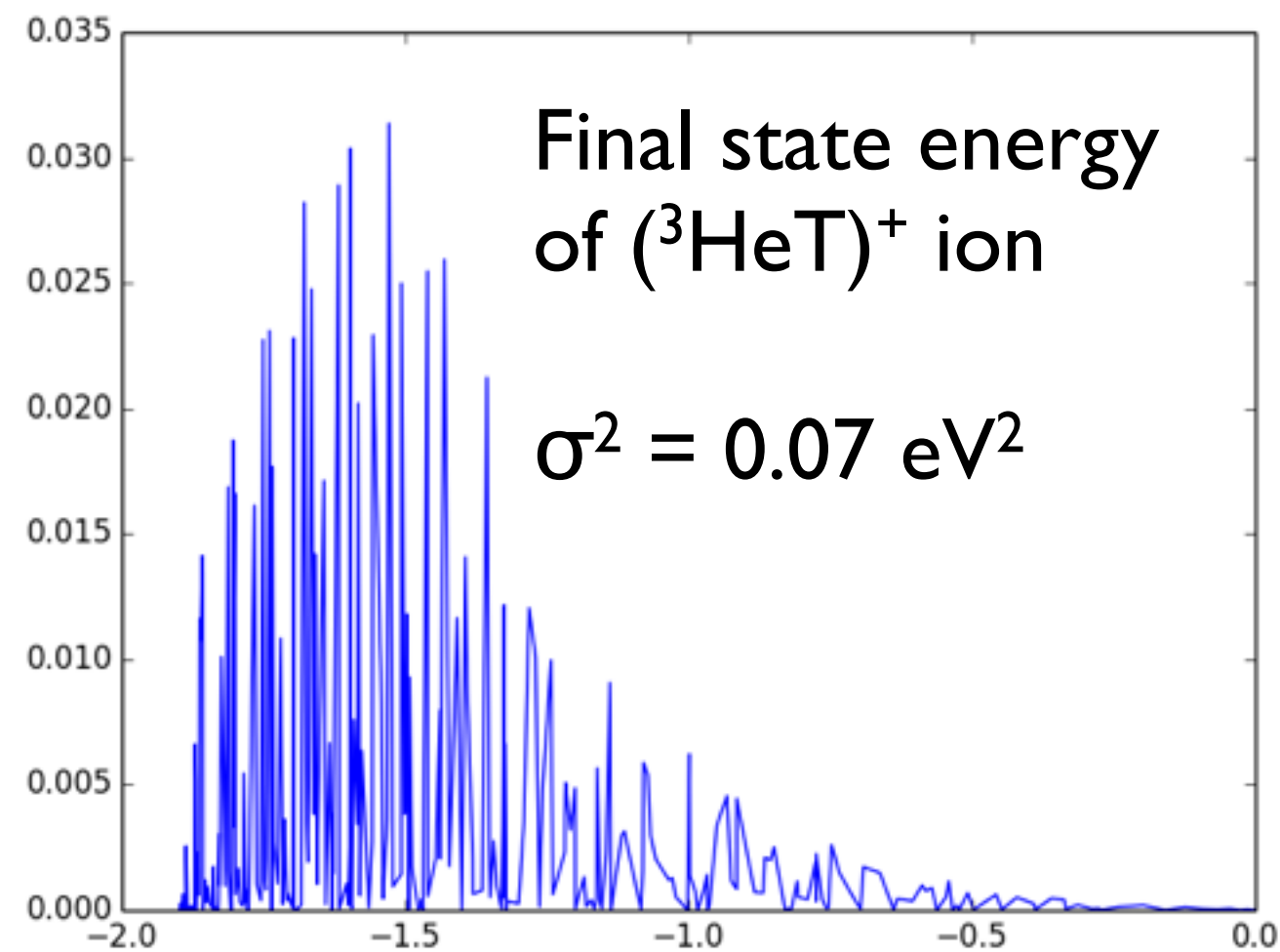
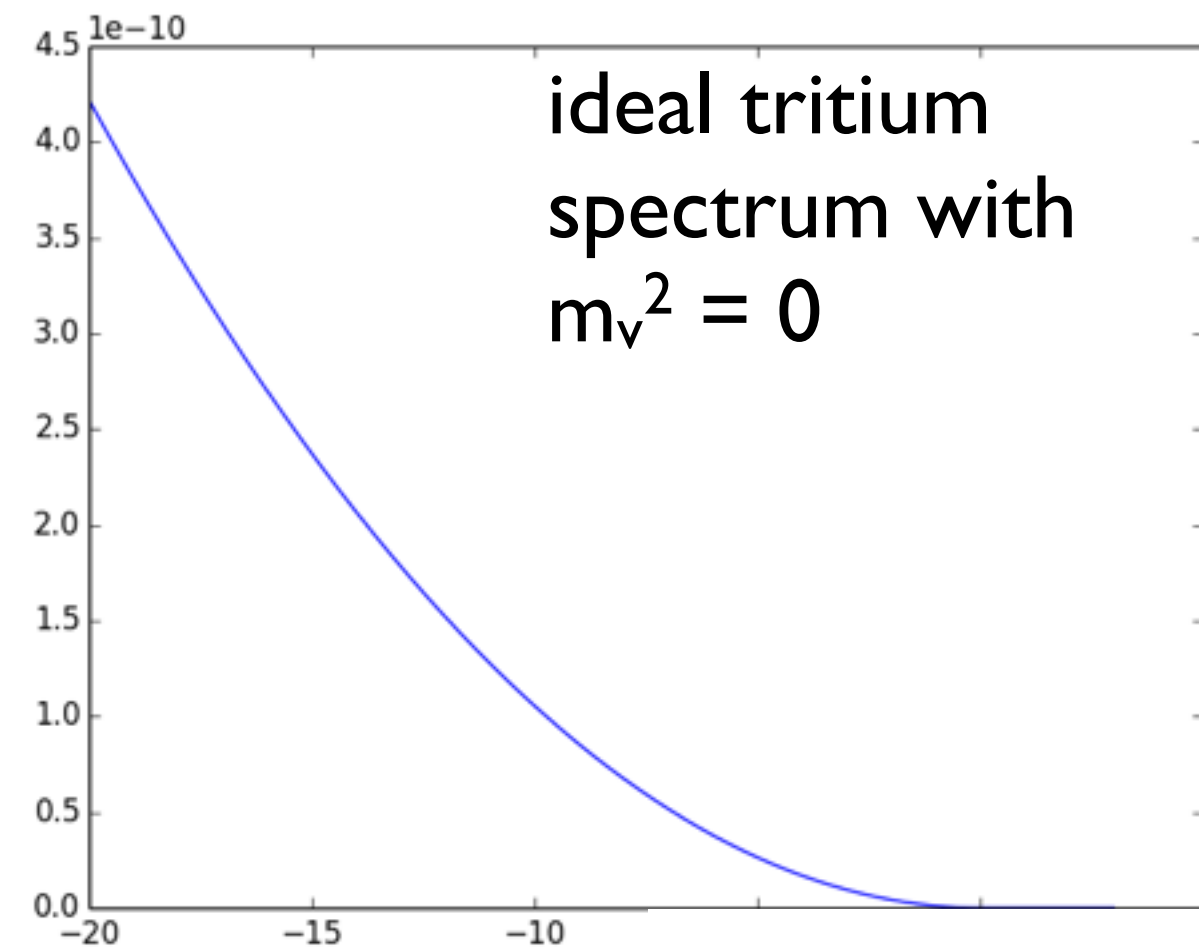


Project 8 sensitivity estimates:

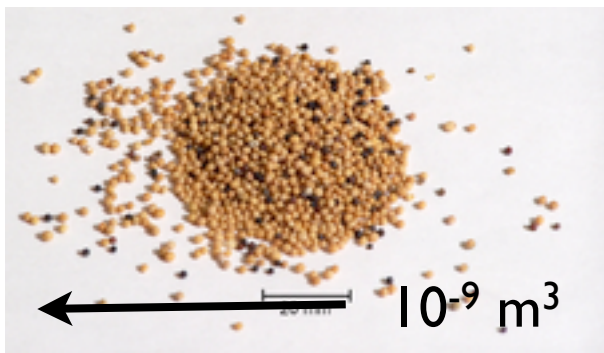
Small and high-density or large and low-density?



Details: B=1 Tesla, background = 1 μ Hz/eV, liveti
pressure broadening known to 1%, field broadening

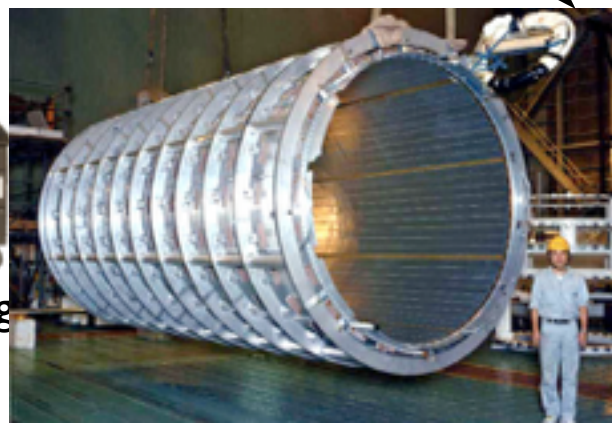
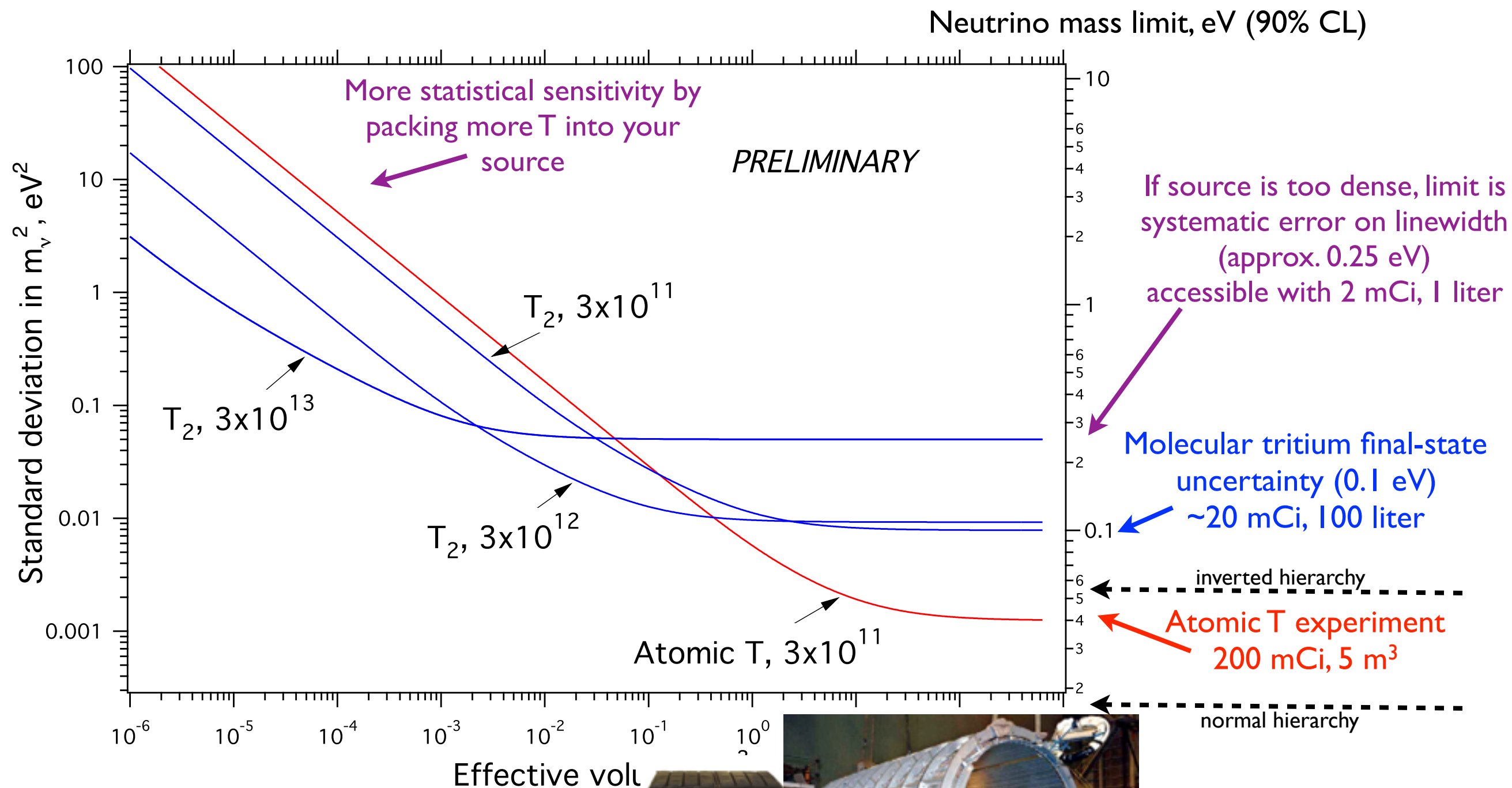


different here,
but usually not
resolvable



Project 8 sensitivity estimates:

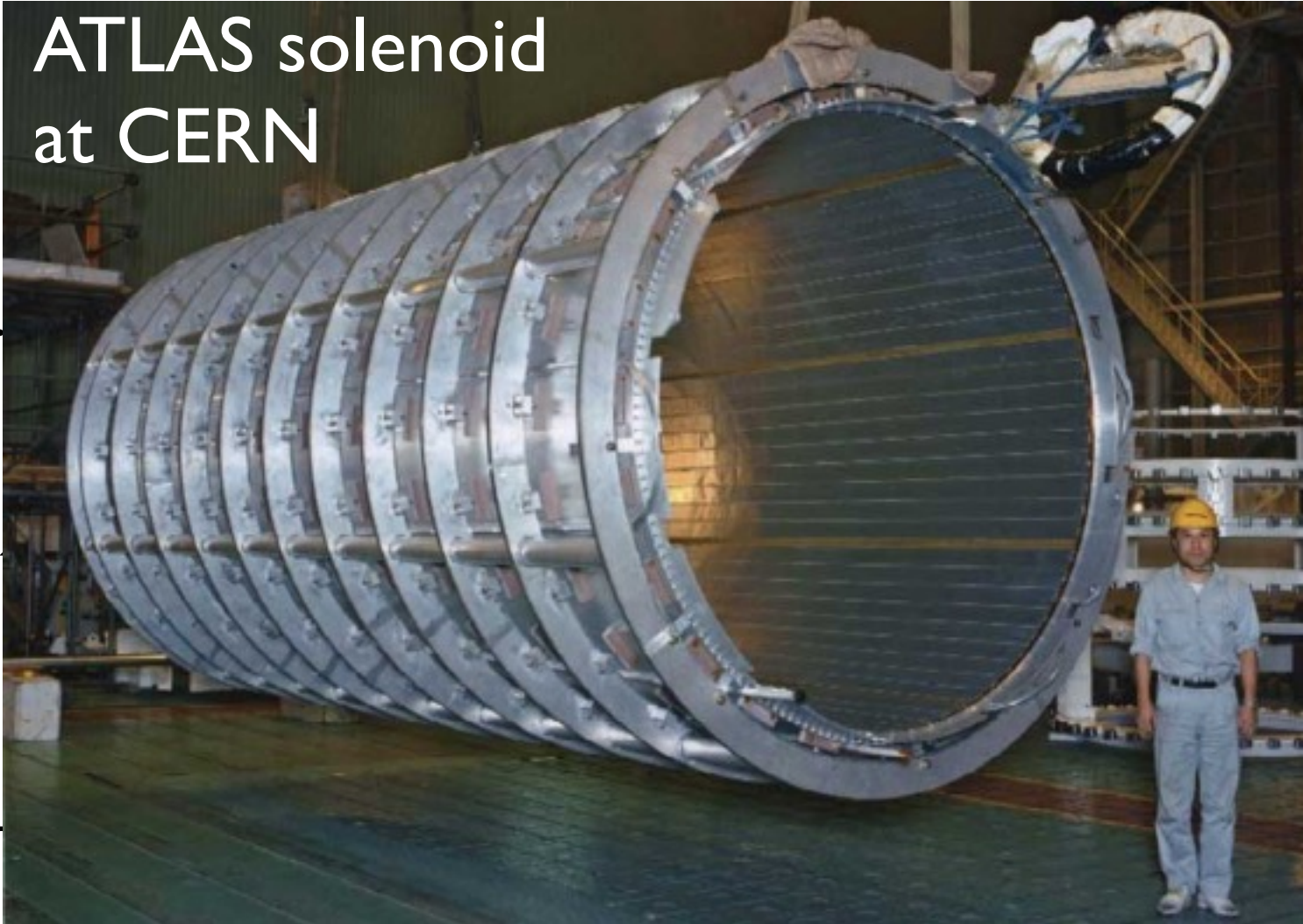
Small and high-density or large and low-density?



Details: B=1 Tesla, background = 1 μ Hz/eV, liveti
pressure broadening known to 1%, field broadening

Scaling up!

- Surprise! The signal $\propto f^2$ dependence deceived us into starting work at high B
- Worse amplifiers and wider bandwidths mean noise $\propto f^2$ too.
- Only problem with low f: size
 - low f = low Δf
 - low Δf = store e^- for long Δt
 - long Δt needs low pressure
 - Boyle's Law $V = I/P$



ATLAS solenoid
at CERN

$f = 1 \text{ GHz}$ $\lambda = 30 \text{ cm}$ $B = 3.8 \text{ kG}$	0.1 Ci 0.3 eV	decay volume 10m long 2.6m diameter	26000 amp-turns per meter	magnetic energy	$1/f$
One giant waveguide with 60 modes	60x channels Noise = 1K	single-mode SNR ~ 6 correlator SNR ~ 50	sensitivity $m\beta = 0.05 \text{ eV}$	number of modes	f

Future Project 8

Phase I

2014 Proof of principle on ^{83m}Kr
Learn by experience

Phase II

2016 T_2 spectrum
First "multi-mode" detection

Phase III

2016— a) atomic tritium R&D
2018 b) antenna array scaleup

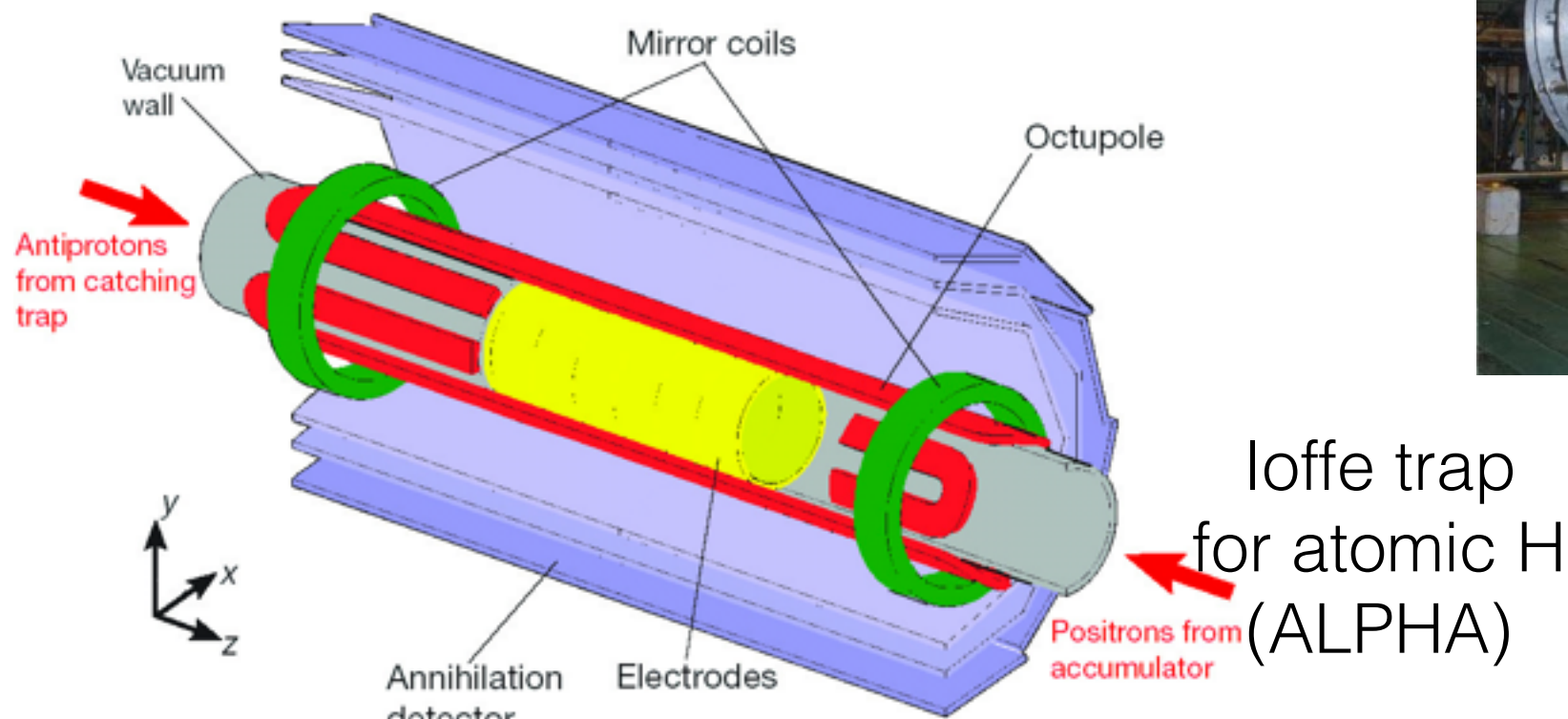
Phase IV

2018— Very large experiment
sensitive below IH scale

ROACH FPGA architecture for DSP



Novel magnet engineering task



- Surplus MRI magnet
- 10^{-6} uniformity in central 50cm
- Now installed at UW and ramped to 1.45T

